APPENDIX B– LITERATURE REVIEW

Bridge engineers have utilized the concept of distribution factors to evaluate the transverse effect of live loads since the 1930's. The distribution of live load shear and moment is crucial to the design of new bridges and to the evaluation of the load carrying capacity of existing bridges. Great efforts have been made to develop simplified methods for live load distribution calculation. Much research has been conducted in order to determine the effect of certain parameters, such as beam spacing, span length, skew angle, etc. The literature review presented in this chapter will cover the following areas: current codes and related articles, international codes, simplified methods of live load distribution, effect of parameters on live load distribution, superstructure modeling, field testing, and non-linear finite element modeling. The references are also sorted by the bridge type each is concerned with.

Current Codes and Related Articles

5. American Association of State Highway and Transportation Officials. *AASHTO Standard Specifications for Highway Bridges*, 16th Edition, Washington, D.C. (1996).

6. American Association of State Highway and Transportation Officials. *AASHTO LRFD Bridge Design Specifications*, 2nd Edition, Washington, D.C. (1998).

8. Aswad, A., and Chen, Y., "Impact of LRFD Specifications on Load Distribution of Prestressed Concrete Girders," PCI Journal, Vol. 39, No. 5 (1994), pp. 78-89.

26. Cai, C.S., Shahawy, M., and Peterman, R.J., “Effect of Diaphragms on Load Distribution of Prestressed Concrete Bridges,” Transportation Research Record, No. 1814, Transportation Research Board, Washington, D.C. (2002), pp. 47-54.

32. Chen, Y., and Aswad, A., “Stretching Span Capability of Prestressed Concrete Bridges Under AASHTO LRFD,” Journal of Bridge Engineering, Vol. 1, No. 3 (August 1996), pp. 112-120.

63. Imbsen, R.A., Liu, W.D., and Schamber, R.A., “Strength Evaluation of Existing Reinforced Concrete Bridges,” National Cooperative Highway Research Program Report 292, Transportation Research Board, Washington, D.C. (1987).

92. Puckett, J.A., “Comparative Study of AASHTO Load and Resistance Factor Design Distribution Factors for Slab-Girder Bridges,” Transportation Research Record No. 1770, Transportation Research Board, Washington, D.C. (2001), pp. 34-37.

112. Shahawy, M., and Huang, D., “Analytical and Field Investigation of Lateral Load Distribution in Concrete Slab-On-Girder Bridges,” ACI Structural Journal, Vol. 98, No. 4 (July/August 2001), pp. 590-599.

120. Song, S.T., Chai, Y.H., and Hida, S.E., “Live Load Distribution in Multi-Cell Box-Girder Bridges and its Comparison with the AASHTO LRFD Bridge Design Specifications,” University of California, Davis, California, Final Report to Caltrans No. 59A0148 (July 2001).

128. Tennessee Department of Transportation, Tennessee Structures Memorandum 043-Lateral Distribution of Structural Loads, Nashville, TN (1996).

132. Tobias, D.H., Anderson, R.E., Khayyat, S.K., Uzman, Z.B., and Riechers, K.L., "Simplified AASHTO LRFD Girder Live Load Distribution in Illinois," Journal of Bridge Engineering (In review).

138. Zokaie, T., "AASHTO-LRFD Live Load Distribution Specifications," Journal of Bridge Engineering, Vol. 5, No. 2 (May 2000), pp. 131-138.

In a paper by Aswad and Chen (8), the impact of the LRFD Specification (6) on the design of prestressed concrete I-beams and spread-box beams in rectangular bridge superstructures was examined. The results showed that the simplified LRFD method yielded smaller distribution factors than the current AASHTO Standard Specifications (5) for interior beams. For interior I-beams, it was further shown that a refined method yielded values that were 4 to 11% smaller than the LRFD method. Finite element analysis showed that the exterior beams carried more live load moment than the first interior beam. The distribution factors were 7 to 15% higher than for the interior beams. The LRFD method has a simplified and conservative procedure for exterior beams; however, its impact had not yet been assessed.

In a study by Chen and Aswad (32) it was shown that a refined method of analysis, i.e. finite element analysis, could reduce the midspan moment by 18-23% for interior I-beams and by 4-12% for exterior I-beams when compared to the AASHTO LRFD (6). A similar reduction was also shown to exist for spread-box beams. Due to this study, it was recommended that a finite element or grillage analysis be used in the case of longer span bridges. In a study of six prestressed concrete bridges, Cai et al. (26) compared the load distribution factors calculated from the AASHTO Standard, the AASHTO LRFD, and field-testing. It was shown that the AASHTO Standard method

overestimated the distribution factors by 17-42%, while the LRFD method overestimated the distribution factors by 14-40%. The differences were attributed to certain factors being ignored in the development of the specifications.

Imbsen et al. (63) examined the accuracy of the AASHTO "S-over" formula for a series of simple span, five-girder T-beam bridges. The grillage method and a semi-analytical procedure were used for the analysis. Both methods gave results that were within 4% of each other. It was shown that the AASHTO values tend to be conservative for an interior girder with girder spacings greater than 8 ft and unconservative for an exterior girder. Concrete slab bridges were also studied using the two methods previously mentioned. Except for span lengths less than about 20 ft, the AASHTO formula seemed to overestimate the wheel line distribution width considerably, which would result in an unconservative design.

Puckett (92) outlined a comparative study of the live load distribution factors for interior beams from a program that employed the finite strip method. The results were compared with those obtained by the NCHRP project 12-26 (141) using the finite element method and those using the AASHTO LRFD (6) formula-based factors. The comparisons were favorable, which further validated the previous work and the AASHTO LRFD distribution factors for interior beams.

Shahawy and Huang (112) compared distribution factors determined from finite element analysis to those calculated from equations in the AASHTO LRFD Specifications (6). It was concluded that the methods prescribed in the Specifications for calculating the load distribution factors for bridges with two or more lanes loaded are satisfactory, provided that the girder spacing and deck overhang do not exceed 8 and 3 ft,

respectively. If these limits are exceeded, errors of up to 30% could be expected. It was also concluded that the AASHTO LRFD load distribution factors for interior and exterior girders of two or more design lanes and for one design lane bridges are too conservative for strength evaluation and rating purposes.

In order to apply the LRFD Specifications (6) to a cast-in-place multicell box bridge, the bridge must have 1) a constant width; 2) parallel beams with approximately equal stiffness; 3) span length of the superstructure exceeding 2.5 times the width, and 4) an angular change of less than 12 degrees in plan, just to name a few. These restrictions became the objective of a study by Song et al. (120). A detailed study was conducted to investigate whether or not these limits could be broadened to include most of the box-girder bridge designs in California. In general, the analysis results from this study indicated that the current LRFD distribution factor formulae for concrete box-girder bridges provide a conservative estimate of the design bending moment and shear force, even for bridges outside the present range of applicability. Results also show that the LRFD formulae are generally more conservative when estimating design forces in the exterior girders, especially for shear forces. When considering a variable-width cross-section, results showed that the LRFD formulae could be used for bridges with a variable-width cross-section with flare up to a ratio of 1-in-16, which is close to the practical geometric limit of 1-in-15. The results seem to suggest that the limit imposed on the plan aspect ratio can be extended to bridges with a deck width equal to its span length. And finally, the plan curvature limit of 12 degrees appeared to be unnecessary, and may be increased to 35 degrees, which was the range studied in this project.

The Tennessee Structures Memorandum (128) outlines the use of Henry's Method. This method for determining lateral distribution of live loads to longitudinal girders was developed by former Engineer of Structures, Henry Derthick and assumes equal distribution to all girders. This method has been shown to yield distribution factors close to those determined by finite element analysis (58).

Tobias et al. (132) explained that in order to facilitate practical implementation of the AASHTO LRFD Specifications (6), engineers at the Illinois Department of Transportation completed an initial interpretation, review and simplification of the LRFD procedure for the design of simply supported and two-span continuous bridges with a typical concrete deck-on-steel girder and concrete deck-on-precast prestressed concrete I-beam cross section. Based on this study, a few of the simplifications, interpretations, and policies that have been set by the State of Illinois for LRFD design are as follows: (1) beam spacings range between 3.5 and 12 ft; (2) span lengths vary from 20 to 240 ft; (3) a minimum of 5 girders must be used in the design of typical bridge superstructures; (4) the ratio of superstructure longitudinal to transverse stiffness term in the basic live load lane distribution equation for moment in typical concrete deck-on-steel girder bridges may be set to 1.02, for typical concrete deck-on-prestressed concrete girder bridges (employing standard Illinois precast sections) the term may be set to 1.10 for I-beams and 1.15 for bulb-tees; (5) the live load lane distribution factor shall not be lower than that for a 240 ft span; (6) the skew correction for end shear in primary bridge beams in the LRFD is reasonable for typical Illinois bridges given the uncertainty surrounding the phenomenon in the field; and (7) typical bridges in Illinois shall be designed for two or more lanes of

loading as opposed to the optional single lane loading except when considering fatigue and shear stud design.

Zokaie (138) presented the background on the development of the AASHTO LRFD distribution factor formulas and compared their accuracy with the S/D method. The formulas were developed from the NCHRP project 12-26. These formulas generally produced results that were within 5% of the results of a finite element deck analysis. The formulas were developed for beam-and-slab bridges with steel, prestressed, or T-beam girders, multicell box girder bridges, side-by-side box beam bridges, solid slab decks, and spread box beam bridges. The models that were used to develop the formulas had uniform spacing, girder inertia, and skew. Continuous models had equal spans and diaphragm effects were not included. The results were calibrated against a database of real bridges with certain ranges of span length, girder inertia, spacing, etc. The formulas were much more accurate than the simple S/D factors, however it was recommend that the LRFD formulas be applied to bridges with similar restraints in order to achieve greater accuracy.

International Codes

27. The Canadian Standards Association, *Canadian Highway Bridge Design Code, 2000 Edition*, Toronto, Ontario, Canada (2000).

66. Japanese Bridge Design Code (2002).

77. Ministry of Transportation and Communications, *Ontario Highway Bridge Design Code* (OHBDC), 2nd Ed., Downsview, Ontario, Canada, (1983).

78. Ministry of Transportation and Communications, *Ontario Highway Bridge Design Code* (OHBDC), 2nd Ed., *Commentary*, Downsview, Ontario, Canada, (1983).

113. Smith, D.S., "Force Effects in Slab-on-Girder Bridge Types at Ultimate and Serviceability Limit States and Recommendations for Live Load Distribution Factors for the Canadian Highway Bridge Design Code," Volumes 1 and 2, Report for New Brunswick Department of Transportation (1996).

114. Smith, D.S., "Force Effects in Slab-on-Girder Bridge Types at the Fatigue and Vibration Limit State and Recommendations for Live Load Distribution Factors for the Canadian Highway Bridge Design Code," Report for New Brunswick Department of Transportation (1997).

115. Smith, D.S., "Force Effects in Slab and Voided Slab Bridge Types at Ultimate and Serviceability Limit States and Recommendations for Live Load Distribution Factors for the Canadian Highway Bridge Design Code," Report for New Brunswick Department of Transportation (1996).

116. Smith, D.S., "Force Effects in Slab and Voided Slab Bridge Types at Fatigue and Vibration Limit State and Recommendations for Live Load Distribution Factors for the Canadian Highway Bridge Design Code," Report for New Brunswick Department of Transportation (1997).

117. Smith, D.S., "Force Effects in Wood Deck on Girder Bridge Types and Recommendations for Live Load Distribution Factors for the Canadian Highway

Bridge Design Code," Report for New Brunswick Department of Transportation (1997).

Lateral distribution of live loads in the Canadian Highway Bridge Design Code (2000) is based on dividing the live load equally between all girders, and then modifying the equal distribution using a factor computed using the bridge properties and a method derived from orthotropic plate theory. A slightly different factor is used for shear and flexure. Excluding timber bridges, there are only two different categorizations of bridges, shallow superstructure and multispine. With the exception of timber bridges, almost all other bridge types fit into one of these categories. Each category has a different distribution factor for the ultimate and serviceability limit states and the fatigue and vibration limit states. The shear and moment modification factors are computed from simple equations selected from a table based on span length and the number of lanes loaded.

The concept of lateral distribution factor is not used in the current Japanese bridge design practice. According to the Japanese Bridge Design Code (66), a stringer/floor beam/main girder structure is generally modeled as a grillage system with a consideration of effective width of deck slab. The live loads are then applied and distributed to stringer/floor beam/girder by performing grillage model analysis. The Japanese Bridge Design Code specifies the live load applications in detail.

David Smith performed a series of parametric studies (113-117) with the intent of modifying the live load distribution factor method for the *Canadian Highway Bridge Design Code* (27). The end product of the research was a distribution factor method based on dividing the total live load equally between all girders and then applying a

modification factor based on the properties of the bridge, including span length, number of lanes loaded, girder location (internal vs. external), girder spacing, and width of the design lane. The new method was compared to the distribution factor method from the 1996 version of the *Canadian Highway Bridge Design Code*. A separate modification factor is used for flexure and shear. In general, bridges are divided into two separate types: shallow superstructure and multispine bridges.

Shallow superstructure bridges include:

- Slab bridges
- voided slab bridges, including multi-cell box girders with sufficient diaphragms
- slab-on-girders
- steel grid deck-on-girders
- wood deck-on-girders
- wood deck on longitudinal wood beams
- stress-laminated wood deck bridges spanning longitudinally
- longitudinal nail-laminated wood deck bridges
- longitudinal laminates of wood-concrete composite decks
- shear-connected beam bridges in which the interconnection of adjacent beams is such as to provide continuity of transverse flexural rigidity across the cross-section

Multispine bridges include:

- box girder bridges in which the boxes are connected by only the deck slab and transverse diaphragms, if present
- shear-connected beam bridges in which the interconnection of adjacent beams is such as not to provide continuity of transverse flexural rigidity across the cross-section

A set of equations was developed for flexure and shear for each bridge type based on two limit state conditions:

- ultimate and serviceability limit states, and
- fatigue and vibration limit states.

The parametric studies by Smith were broken down as follows:

- Slab-on-girder bridges at ultimate and serviceability limit states (113). The parametric study included approximately 550 bridges with varying structure width, number of lanes loaded, span length, number of girders, girder spacing, girder moment of inertia, and lane width.
- Slab-on-girder bridges at fatigue and vibration limit states (114). The parametric study included approximately 600 bridges with varying structure width, number of lanes loaded, span length, number of girders, girder spacing, girder moment of inertia, and lane width.
- Slab and voided slab bridges at the ultimate and serviceability limit states (115). The parametric study included approximately 100 slab and voided slab bridges with varying structure width, number of lanes loaded, span length,

slab thickness, number of voids (for voided slab bridges), web spacing, and web thickness.

- Slab and voided slab bridges at the fatigue and vibration limit state (116). The parametric study included 40 slab and voided slab bridges with varying structure width, number of lanes loaded, span length, slab thickness, number of voids (for voided slab bridges), web spacing, and web thickness.

- Wood deck on girder bridges at the ultimate, serviceability, fatigue, and vibration limit states (117). The parametric study included approximately 120 bridges with varying structure width, number of lanes loaded, span length, number of girders, girder spacing, girder moment of inertia, deck thickness, and lane width.

Simplified Methods

4. Amer, A., Arockiasamy, M., and Shahawy, M., "Load Distribution of Existing Solid Slab Bridges Based on Field Tests," Journal of Bridge Engineering, Vol. 4, No. 3 (August 1999), pp. 189-193.

7. Arockiasamy, M., and Amer, A., "Load Distribution on Highway Bridges Based on Field Test Data," Final Report, Florida DOT HPR Study No. 0668, WPI 0510668, Job No. 99500-3512-119, Center for Infrastructure and Constructed Facilities, Florida Atlantic University, Boca Raton, Florida (1995).

9. Aziz, T.S., Cheung, M.S., and Bakht, B., "Development of a Simplified Method of Lateral Load Distribution for Bridge Superstructures," Transportation Research

Record No. 665, Transportation Research Board, Washington, D.C. (1978), pp. 37-44.

13. Bakht, B., and Jaeger, L.G., “Effect of Vehicle Eccentricity on Longitudinal Moments in Bridges,” Canadian Journal of Civil Engineering, Vol. 10, No. 4 (December 1983), pp. 582-599.

14. Bakht, B., and Jaeger, L.G., “Simplified Methods of Bridge Analysis for the Third Edition of OHBDC,” Canadian Journal of Civil Engineering, Vol. 19, No. 4 (August 1992), pp. 551-559.

15. Bakht, B., and Moses, F., “Lateral Distribution Factors for Highway Bridges,” Journal of Structural Engineering, Vol. 114, No. 8 (August 1988), pp. 1785-1803.

16. Bakht, B., Cheung, M.S., and Aziz, T.S., “Application of a simplified method of calculating longitudinal moments to the Ontario highway bridge design code,” Canadian Journal of Civil Engineering, Vol. 6, No. 1 (March 1979), pp. 36-50.

17. Bakht, B., Jaeger, L.G., and Cheung, M.S., “Transverse Shear in Multibeam Bridges,” Journal of Structural Engineering, Vol. 109, No. 4 (April 1983), pp. 936-949.

30. Chen, Y., “Refined and Simplified Methods of Lateral Load Distribution for Bridges with Unequally Spaced Girders: I. Theory,” Computers and Structures, Vol. 55, No. 1 (April 1995), pp. 1-15.

31. Chen, Y., “Refined and Simplified Methods of Lateral Load Distribution for Bridges with Unequally Spaced Girders: II. Applications,” Computers and Structures, Vol. 55, No. 1 (April 1995), pp. 17-32.

35. Culham, G.A., and Ghali, A., “Distribution of Wheel Loads on Bridge Girders,” Canadian Journal of Civil Engineering, Vol. 4, No. 1 (March 1977), pp. 57-65.

36. Davis, R.E., Bon, V.D., and Semans, F.M., “Live Load Distribution in Concrete Box-Girder Bridges,” Transportation Research Record, No. 871, Transportation Research Board, Washington, D.C. (1982), pp. 47-52.

51. Goodrich, B.L., “Simplified Method for Determining Live Load Distribution Factors for Overweight Vehicles with Non-Standard Axle Configurations,” M.S. Thesis, University of Wyoming, Laramie, WY (1999).

52. Goodrich, B.L., and Puckett, J.A., “Simplified Load Distribution for Vehicles with Nonstandard Axle Gages,” Transportation Research Record No. 1696, Vol. 2, Transportation Research Board, Washington, D.C. (April, 1999), pp. 158-170.

57. Heins, C.P., “Influence of Bracing on Load Distribution of Bridges,” International Conference on Short and Medium Span Bridges, Toronto (1982), pp. 3-15.

60. Huo, X.S., Wasserman, P.E., Zhu, P., “A Simplified Method of Lateral Distribution of Live Load Moment,” Journal of Bridge Engineering (2002) (in press).

62. Imbsen, R.A., and Schamber, R.A., “Influence Surface Approach to Determine Wheel Load Distribution Factors for Rating Highway Bridges,” International Conference on Short and Medium Span Bridges, Proceedings, Toronto, Canada (1982), pp. 273-287.

65. Jaeger, L.G., Bakht, B., and Cheung, M.S., “Characterizing Parameters for Grillages and Orthotropic Plates,” Journal of the Institution of Engineers (India), Vol. 66, No. 3,4 (1986), pp. 150-157.

82. Moses, F., and Verma, D., “Load Capacity Evaluation of Existing Bridges,” National Cooperative Highway Research Program Report 301, Transportation Research Board, Washington, D.C., 1987.

84. Normandin, P., and Massicotte, B., “Load Distribution in Composite Steel Box Girder Bridges,” Developments in Short and Medium Span Bridge Engineering (1994), pp. 165-176.

93. Puckett, J.A., and Goodrich, B.G., “Simplified Approach for Live Load for Permit Vehicles with Non-Standard Axle Gages, Bridge Software Validation Guidelines,” Transportation Research Record No. 1696, Vol. 2, Transportation Research Board, Washington, D.C. (April 2000), pp. 143-151.

104. Samaan, M., Sennah, K., and Kennedy, J.B., “Distribution of Wheel Loads on Continuous Steel Spread-Box Girder Bridges,” Journal of Bridge Engineering, Vol. 7, No. 3 (May/June 2002), pp. 175-183.

106. Sanders, W.W., Jr., and Elleby, H.A., “Distribution of Wheel Loads on Highway Bridges,” National Cooperative Highway Research Program Report No. 83, Transportation Research Board, Washington, D.C. (1970).

107. Schilling, C.H., “Lateral Distribution Factors for Fatigue Design,” Journal of the Structural Division, Vol. 108, No. ST9 (September 1982), pp. 2015-2033.

111a. Sennah, K.M., and Kennedy, J.B., "Load Distribution Factors for Composite Multicell Box Girder Bridges," Journal of Bridge Engineering, Vol. 4, No. 1 (February 1999), pp. 71-78.

111b. Samaan, M., Sennah, K., and Kennedy, J.B., "Distribution Factors for Curved Continuous Composite Box-Girder Bridges," Journal of Bridge Engineering, Vol. 10, No. 6, November 2005, pp. 678 – 692.

112. Shahawy, M., and Huang, D., "Analytical and Field Investigation of Lateral Load Distribution in Concrete Slab-On-Girder Bridges," ACI Structural Journal, Vol. 98, No. 4 (July/August 2001), pp. 590-599.

125. Tabsh, S.W., and Tabatabai, M., "Live Load Distribution in Girder Bridges Subject to Oversized Trucks," Journal of Bridge Engineering, Vol. 6, No. 1 (January/February 2001), pp. 9-16.

127. Tarhini, K.M., and Frederick, G.R., "Wheel Load Distribution in I-Girder Highway Bridges," Journal of Structural Engineering, Vol. 118, No. 5 (May 1992), pp. 1285-1295.

141. Zokaie, T., Osterkamp, T.A., and Imbsen, R.A., "Distribution of Wheel Loads on Highway Bridges," NCHRP 12-26 Project Final Report, Vol. 1, Transportation Research Board, National Research Council, Washington, D.C. (1991).

Amer et al. (4) discussed the results for solid slab bridges from a study by Arockiasamy and Amer (7). The development of equations to determine the equivalent widths of solid slab bridges was explained. It was shown from the study that the bridge width could be neglected as a parameter. Also, it was shown that slab thickness had little

effect on the equivalent width, which confirmed the approaches adopted by the AASHTO Standard and AASHTO LRFD codes. Arockiasamy and Amer (7) also tested slab-on-girder bridges and double tee beam bridges. Simplified equations were developed for shear load distribution of slab-on-girder bridges.

Aziz et al. (9) presented a simplified method for establishing live load moments in most common types of bridges. This method has since been used in Canadian bridge design codes. This simplified method follows a similar approach to the AASHTO Standard Specifications. The distribution factor is determined by dividing the girder spacing, S by a constant, D. The simplified method presented utilizes charts that are based on the torsional and flexural stiffness of the bridge in order to determine the constant, D. Separate charts were developed for 2, 3, and 4 lane bridges in addition to a correction factor chart. In all cases considered, the simplified method yielded distribution factors that were safe but economical. It was believed that this method would provide more accurate load distribution than the AASHTO and CSA-S6 codes while maintaining the simplicity of an AASHTO-type approach. This simplified approach was also discussed by Bakht et al. (16) and Bakht and Moses (15). The derivation of the characterizing parameters that are use in the simplified methods of analysis are presented by Jaeger et al. (65).

A simplified method to account for increased vehicle edge distance was presented by Bakht and Jaeger (13). It was demonstrated that the vehicle edge distance has a significant effect on load distribution in bridges. Simplified analyses based on a fixed vehicle edge distance are very conservative. The purpose of this method was to provide a modifier for longitudinal moments obtained by the AASHTO (1979) and OHBDC (1983)

simplified methods. The validity of this simplified semi-graphical method was confirmed with field test results.

The third edition of the OHBDC has incorporated simplified methods for load distribution calculations. Bakht and Jaeger (14) discussed these simplified methods along with their developmental background. With respect to live load distribution, the semi-graphical nature of the first two editions of the OHBDC was discarded due to discrepancies between the readings taken by difference people. Therefore, the parameters for the simplified methods are in terms of expressions rather than graphs. The expressions are simple and have been checked extensively and found to give results that are comparable in accuracy to those given by the α-θ method, which has already been checked and found to compare well with the rigorous methods of analysis. Bakht et al. (17) discussed a simplified method for determining transverse shear intensity in the shear keys of multi-beam bridges due to the AASHTO and Ontario highway bridge design vehicles.

Culham and Ghali (35) presented a simple empirical formula for reinforced and prestressed concrete T- and I-girder bridges. The empirical formula showed good correlation with computer results. It was suggested that the simple span distribution approach be abandon because it underestimates the wheel loads taken by the exterior girders. It was said that a consistently conservative result would be achieved if the exterior girder distribution factors were determined by the same formula presented for interior girders.

Davis et al. (36) presented an alternate design method, which employed nomographic analysis for traditional designs and influence line analysis for hybrid

loadings. This alternate design method, while reasonably accurate, was very limited in its applicability to different bridge types and geometries.

Goodrich and Puckett (52) developed a simplified method to determine the live load distribution factors for moment and shear for vehicles with nonstandard axle configurations. The current AASHTO LRFD distribution factor formulas were incorporated into some of the simplified method formulas and in other cases, the lever rule and rigid methods were used. Generally, the developed formulas were conservative. When compared to the rigorous results, the results from the simplified method for the interior girders were more accurate than those for the exterior girders.

Heins (57) conducted a study on the influence of bracing on load distribution of straight and curved bridges. The effects of bracing were determined by examining the response of single and continuous span, multigirder, skew and radially supported, composite bridges of span lengths varying from 80 to 300 ft, with girder spacings of 6, 10, and 14 ft. The results of this study were used to develop a series of design equations. The equations were to be used in conjunction with the AASHTO 12th edition bridge design code.

Huo et al. (60) introduced a simplified method known as Henry's method, which has been used in Tennessee for nearly four decades. This method assumes equal distribution to all supporting members. Distribution factors determined from the simplified method were compared with those from the AASHTO Standard (5), the AASHTO LRFD (6), and finite element analysis. In the cases studied, distribution factors from Henry's method were slightly higher than from finite element analysis, but compared well with the AASHTO LRFD. A modification factor based on the

superstructure type was suggested, which would make the simplified method more accurate.

Imbsen and Schamber (62) described a method for determining wheel load distribution factors by using an influence surface approach. It was noted that girder spacing and span length are the primary variables that affect the maximum amplitude of an influence surface. It was also discovered that the influence surfaces generated for a five-girder system could be used for bridges having more than five girders. Standardized influence surfaces were developed for a family of T-beam bridges. The influence surfaces were developed by normalizing longitudinal and transverse effects so that the entire family of T-beam bridges could be represented by a minimum number of influence surfaces.

Moses and Verma (82) presented correction factors that should be applied to distribution factor values when evaluating existing bridges. The correction factors were broken down into four categories: 1) AASHTO distribution; 2) tabulated analysis with simplifying assumptions; 3) sophisticated analysis, including finite element, orthotropic plate, and grillage analogy; and 4) field measurements. The correction factors reflect the possible uncertainties in the measurement or analytical model.

A simplified approach for computing bending moment and shear in composite steel-concrete box girder bridges was proposed for the Canadian Highway Bridge Design Code by Normandin and Massicotte (84). This simplified approach was developed in order to replace the S/D method that is utilized in some bridge design codes, such as CSA-S6 (1988) and OHBDC (1991). The proposed method was based on a concept in which the total vehicle (or the full uniform load) would be used in a 2-dimensionl

analysis. Also, the total live load with all lanes loaded would be applied on the bridge. The average load effects are determined by dividing the total load by the number of supporting elements. The actual load effects are obtained by multiplying the average effects by a modification factor, which must be larger than one. Separate modification factors exist for moment and shear. This method was said to be applicable to any bridge type, avoids errors related to empirical relationships, and instructs the designer on the relative stiffness of the bridge structure. The equations for the proposed method were developed for simply supported bridges where the width of the steel section is of the same order of magnitude as the lane width. Interior diaphragms at quarter points are an absolute restriction to the applicability of the equations. And finally, all box girder webs are assumed to be equally distributed across the bridge width. The simplified method gave more reliable and more uniform results than the methods specified in bridge design codes.

Samaan et al. (104) focused on continuous composite concrete-steel spread-box girder bridge distribution factors. In their study, 60 continuous bridges with various numbers of cells, roadway widths, span lengths, and cell geometries were subjected to AASHTO HS 20-44 truck and lane loadings. The finite element modeling was carried out using the ABAQUS software. The two equal-span bridges evaluated in this study were limited to a span-to-depth ratio of 25, which has been shown to be the most economical. Formulas to calculate the distribution factor for maximum positive and negative stress in the bottom flange along the span were developed. The formulas require the number of lanes, span length, and number of beams. A formula to calculate the distribution factor for maximum shear was also developed with the same parameters as for stresses.

However, the study does not include the effect of different span lengths in continuous bridges, or bridges of more than two spans. Additionally, no provisions are made for skew or curvature, and results are limited to steel spread-box girder bridges.

Sanders and Elleby (106) proposed revisions to the 1965 edition of the AASHTO Standard that dealt with the distribution of loads in highway bridges. The revisions were based on a study that was limited to short- and medium-span bridges of the following types: slab, beam and slab, multi-beam and concrete box girder. The major variables that were found to affect the load distribution in each of the major bridge types were: relative flexural stiffness in longitudinal and transverse directions, relative torsional stiffness in the same directions, bridge width, and effective bridge span. All of these variables were considered in the relationships developed. The proposed changes did not significantly affect the current designs during that time. However, the changes did make the designs more realistic and considered the benefits derived from improving bridge properties.

A convenient and conservative chart for lateral distribution factors for fatigue was developed in a study by Schilling (107). This chart could be used to obtain upper-limit factors for both interior and exterior beams to make an initial fatigue check. Distribution factors from the chart were in good agreement with factors determined from field measurements.

Composite steel-concrete multicell box girder bridges were the focus of a study done by Sennah and Kennedy (111a) to determine a more practical and simple method of developing distribution factors. Using a finite element method with ABAQUS software, 120 bridges of various geometries were analyzed. The research studied the effects of number of cells, cell geometries, span length, number of lanes, and cross bracings.

AASHTO HS 20-44 truck load, lane loads, and bridge dead loads were considered. Separate expressions to calculate distribution factors were developed for shear and moment and compared to a simply supported composite concrete deck-steel three-cell bridge model. The proposed expressions were shown to be highly accurate and could be beneficial to the design of steel-concrete multicell box girder bridges. However, these expressions are strictly limited to this specific type of construction.

A November 2005 ASCE paper by Samaan, Sennah, and Kennedy (111b) presents a simplified method for computing distribution factors for steel tub girder bridges. The recommendations in this research are based on a formalized parametric study using finite element models verified by comparison to experimental results. For straight, right bridges, the simplified formula takes the form of $g = \left(\frac{4}{N_L}\right)^{Exp}$, where N_L is the number of lanes loaded, and *Exp* is a constant that varies for the action being considered.

The study considered 240 continuous tub girder bridges of varying plan geometries and cross section dimensions. Of these, 60 are straight bridges, and the remainder are curved in plan. We are currently entering the geometries of the 60 straight bridges for analysis with the lever rule, uniform distribution, parametric formula methods, as well as the method proposed by Samaan et al. The finite element distribution factors have been requested from Dr. Sennah, and if they become available for comparison, they will be used as the rigorous distribution factors. If they are not available, these bridges will be analyzed using grillage methods to be verified by comparison to finite element models similar to those used in the study (2). Due to the

thorough and systematic approach used in the study, it is hoped that the finite element model distribution factors are available for our use. Two existing US bridges have been modeled using grillage and finite element techniques in SAP 2000. These models (and others) will be used, if necessary, to validate an independent grillage approach.

Shahawy and Huang (112) proposed modifications to the AASHTO LRFD (6) distribution formulas. These modifications resulted in distribution factors that were very close to results obtained from finite element analysis and field-testing. These modifications were therefore recommended for strength evaluation and load rating purposes.

Tabsh and Tabatabai (125) created modification factors for bridges subject to oversized trucks, which could be applied to any specification-based distribution factor. The research utilized finite element methods to evaluate flexure and shear due to HS20, OHBDC, PennDOT, and HTL-57 truck loadings. The effects of truck configuration and gauge widths were investigated in the study. Three different single span lengths, each with three different girder spacings, and each with composite steel superstructures were considered. For each span length, different slab thicknesses along with a different number of beams were examined resulting in a total of nine bridges. Two gauge modification factors were developed, one for moment and one for shear. The modification factors are dependent upon girder spacing and gauge width. For multiple loaded lanes, the live load moment in an interior girder is to be determined by multiplying the oversized truck effect by the developed GDF for one lane of loading and then adding it to it the product of specification-based GDF expressions for multiple and one lane of loading. The study is limited to simple span bridges consisting of a concrete

slab on composite steel girders. In addition to the limited superstructure type, the three different span lengths considered varied from only 48 ft to 144 ft. For different types of construction, much longer span lengths are possible and could cause more prominent effects on results.

Tarhini and Frederick (127) did a comparative study examining the wheel load distribution factors in I-girder bridges. Using the basic principles of the current AASHTO S/5.5 distribution factors, a new equation was developed based on data produced by ICES STRUDL II finite element models. A typical bridge design was selected, and one parameter was allowed to vary at a time. The parameters considered were the size and spacing of steel girders, presence of cross bracing, concrete slab thickness, span length, single and continuous spans, and composite and noncomposite behavior. However, the quadratic equation developed is based only on span length and girder spacing and yields accurate results only for single, or two-lane loading of non-skewed, single span bridges, and continuous span bridges with equal span lengths.

Effect of Parameters on Live Load Distribution

The literature reviewed in this section deals with the following items and their impact of live load distribution:

- diaphragms
- barriers
- slab thickness
- beam spacing
- number of beams

- span length
- skew angle

1. Abenroth, R.E., Klaiber, F.W., and Shafer, M.W., “Diaphragm Effectiveness in Prestressed Concrete Girder Bridges,” Journal of Structural Engineering, Vol. 121, No. 9 (September 1995), pp.1362-1369.

2. Abenroth, R.E., Klaiber, F.W., and Shafer, M.W., “Lateral Load Resistance of Diaphragms in Prestressed Concrete Girder Bridges,” Final Report, Iowa DOT Project HR-319, ISU-ERI-Ames-92076, Engineering Res. Inst., Iowa State Univ., Ames, Iowa (1991).

9. Aziz, T.S., Cheung, M.S., and Bakht, B., “Development of a Simplified Method of Lateral Load Distribution for Bridge Superstructures,” Transportation Research Record No. 665, Transportation Research Board, Washington, D.C. (1978), pp. 37-44.

10. Azizinamini, A., Kathol, S., and Beacham, M.W., “Influence of Cross Frames on Load Resisting Capacity of Steel Girder Bridges,” Engineering Journal, Vol. 32, No. 3 (Third Quarter 1995), pp. 107-116.

21. Barr, P.J., Eberhard, M.O., and Stanton, J.F., “Live-Load Distribution Factors in Prestressed Concrete Girder Bridges,” Journal of Bridge Engineering, Vol. 6, No. 5 (September/October 2001), pp. 298-306.

26. Cai, C.S., Shahawy, M., and Peterman, R.J., “Effect of Diaphragms on Load Distribution of Prestressed Concrete Bridges,” Transportation Research Record, No. 1814, Transportation Research Board, Washington, D.C. (2002), pp. 47-54.

34. Cheung, M.S., Jategaonkar, R., and Jaeger, L.G., "Effects of Intermediate Diaphragms in Distributing Live Loads in Beam-and-Slab Bridges," Canadian Journal of Civil Engineering, Vol. 13, No. 8 (September 1986), pp. 278-292.

35. Culham, G.A., and Ghali, A., "Distribution of Wheel Loads on Bridge Girders," Canadian Journal of Civil Engineering, Vol. 4, No. 1 (March 1977), pp. 57-65.

37. Eamon, C.D., and Nowak, A.S., "Effects of Edge-Stiffening Elements and Diaphragms on Bridge Resistance and Load Distribution," Journal of Bridge Engineering, Vol. 7, No. 5 (September/October 2002), pp. 258-266.

45. Foinquinos, R., Kuzmanovic, B., and Vargas, L.M., "Influence of Diaphragms on Live Load Distribution in Straight Multiple Steel Box Girder Bridges," Proc., 15th Structures Congress, Portland, OR, Vol. 1 (April 1997), pp. 89-93.

54. Green, T., Yazdani, N., Spainhour, L., and Cai, C.S., "Intermediate Diaphragm and Temperature Effects on Concrete Bridge Performance," Transportation Research Record No. 1814, Transportation Research Board, Washington, D.C. (2002), pp. 83-90.

67. Kennedy, J.B., and Grace, N.F., "Load Distribution in Continuous Composite Bridges," Canadian Journal of Civil Engineering, Vol. 10, No. 3 (September 1983), pp. 384-395.

73. Mabsout, M.E., Tarhini, K.M., Frederick, G.R., and Kesserwan, A., "Effect of Continuity on Wheel Load Distribution in Steel Girder Bridges," Journal of Bridge Engineering, Vol. 3, No. 3 (August 1998), pp. 103-110.

74. Mabsout, M.E., Tarhini, K.M., Frederick, G.R., and Kesserwan, A., “Effect of Multilanes on Wheel Load Distribution in Steel Girder Bridges,” Journal of Bridge Engineering, Vol. 4, No. 2 (May 1999), pp. 99-106.

75. Mabsout, M.E., Tarhini, K.M., Frederick, G.R., and Kobrosly, M., “Influence of Sidewalks and Railings on Wheel Load Distribution in Steel Girder Bridges,” Journal of Bridge Engineering, Vol. 2, No. 3 (August 1997), pp. 88-96.

80. Moore, M., Strand, K.A., Grubb, M.A., and Cayes, L.R., “Wheel-Load Distribution Results from AISI-FHWA Model Bridge Study,” Transportation Research Record No. 1275, Transportation Research Board, Washington, D.C. (1990), pp. 34-44.

81. Modjeski and Masters, Inc., “Shear in Skewed Multi-Beam Bridges,” NCHRP 20-07/Task 107 Final Report, Transportation Research Board, National Research Council, Washington, D.C. (March 2002).

84. Normandin, P., and Massicotte, B., “Load Distribution in Composite Steel Box Girder Bridges,” Developments in Short and Medium Span Bridge Engineering (1994), pp. 165-176.

101. Ramaiah, S.R., Seyedmadani, N.A., and Oliden, O.A., “Finite Element Modeling, Analysis, and Design of Highly Skewed Post-Tensioned Concrete Bridges,” Transportation Research Record No. 1290, Transportation Research Board, Washington D.C. (1991), pp.144-151.

103. Sadler, C., and Holowka, M., “Edge-Stiffening Effect of New Jersey Barrier Walls on Cantilever Slabs,” Transportation Research Record No. 950, Vol. 2, Transportation Research Board, Washington, D.C. (1984), pp. 75-84.

107. Schilling, C.H., “Lateral Distribution Factors for Fatigue Design,” Journal of the Structural Division, Vol. 108, No. ST9 (September 1982), pp. 2015-2033.

109. Sengupta, S., and Breen, J.E., “The Effect of Diaphragms in Prestressed Concrete Girder and Slab Bridges,” Res. Report 158-1F, Project 3-5-71-158, Center for Highway Res., Univ. of Texas at Austin, TX (1973).

111. Sennah, K.M., and Kennedy, J.B., “Load Distribution Factors for Composite Multicell Box Girder Bridges,” Journal of Bridge Engineering, Vol. 4, No. 1 (February 1999), pp. 71-78.

118. Smith, K.N., and Mikelsteins, I., “Load Distribution in Edge Stiffened Slab and Slab-on-Girder Bridge Decks,” Canadian Journal of Civil Engineering, Vol. 15, No. 6 (December 1988), pp. 977-983.

119. Soliman, M., and Kennedy, J.B., “Load Distribution in Composite Bridges at the Ultimate Limit State,” Developments in Short and Medium Span Bridge Engineering, Vol. 1 (1990), pp. 201-214.

121. Stallings, J.M., Cousins, T.E., and Stafford, T.E., “Removal of Diaphragms from Three-Span Steel Girder Bridge,” Journal of Bridge Engineering, Vol. 4, No. 1 (February 1999), pp. 63-70.

Abenroth et at. (1,2) conducted a study that included testing a full-scale, simple span, precast concrete (P/C) girder bridge model with eight intermediate diaphragm

configurations. A model without diaphragms was also tested. The primary objectives of this research were to determine the effectiveness of intermediate reinforced concrete and steel diaphragms and to determine whether steel diaphragms of some conventional configurations were essentially structurally equivalent to the cast-in-place reinforced concrete diaphragms presently being used by the Iowa DOT. The bridge model was analyzed using the ANSYS finite element program. The P/C girders and deck where modeled by using solid elements with eight nodes and three degrees of freedom at each node. The deck was modeled as a single layer of elements that were arranged in a rectangular pattern. Each girder cross section was modeled using six elements. When reviewing the results it was found that the vertical load distribution was essentially independent of the diaphragm type and location. Girder rotational end restraint (pinned or fixed) resulted in a variation of the vertical load distribution factor of approximately 10% on the loaded girder. The range in the distribution factors decreased in girders that were further away from the loaded girder. When a horizontal load was applied to the first P/C girder and the steel channel diaphragms were in place, approximately 15% to 25% of the horizontal force was distributed to girder on the opposite side. Similar results were obtained in the theoretical investigation. The X-brace plus strut diaphragm distributed about 30% of the horizontal load, while the X-brace without strut diaphragm distributed about 20% of the horizontal load. It was concluded that construction details at the P/C girder supports resulted in significant rotational end restraint for both vertical and horizontal loading. The vertical load distribution was essentially independent of the type and location of intermediate diaphragms, while the horizontal load distribution was a function of diaphragm type and location. It was also shown that the X-brace plus strut

intermediate diaphragms were essentially structurally equivalent to the R/C intermediate diaphragms.

Aziz et al. (9) in a study to develop a simplified method for determining live load distribution factors explained the effect several variables had on lateral load distribution. The bridge width was said to affect bridge behavior because bridges with smaller aspect ratios usually tend to have better load distribution characteristics. The number of lanes also affects load distribution in that more loaded lanes cause girders to share the load more equally and thus the moment distribution in the transverse direction becomes more uniform. The longitudinal axle spacing was found to have very little effect on the transverse load distribution. It was stated that as long as the axle width was standard (6 ft), distribution factors for a particular axle spacing could be used for any other type of truck configuration without sacrificing accuracy within practical limits. Another factor said to affect load distribution is continuity, however, the researchers stated that continuity only affects the absolute values of the moments. The moment distribution pattern is not affected by continuity. A required adjustment for continuous bridges is to utilize the effective span (distance between contraflexure points) when calculating the flexural stiffness for the simplified method.

The influence of cross frames of steel girder bridges was investigated by Azizinamini et al. (10). It was concluded that although cross frames may be needed during construction, their presence has little influence on the behavior of steel bridges after construction. Results showed that the cross frames were to some degree harmful because they try to prevent the small tendency of the girders to separate during elastic ranges, which consequently transfers restraining forces to the girder webs. These

restraining forces have been shown to cause cracking. After construction, the stiffness of the slab is sufficient enough to distribute the live load to adjacent girders.

Barr et al. (21) presented an evaluation of flexural live load distribution factors for a series of three-span prestressed concrete girder bridges. The finite element models were used to evaluate the procedures for computing flexural live load distribution factors that are embodied in bridge design codes. These finite element models were also used to investigate the effects that lifts (haunches in the slab directly over the girders), intermediate diaphragms, end diaphragms, continuity, and skew angle have on distribution factors. The finite element analysis was carried out using SAP2000. It was shown that on average, the addition of the lift reduced the distribution factors by 17% for the exterior girders and by 11% for the interior girders, however, the LRFD distribution factors increased by 1%. For both interior and exterior girders, the addition of intermediate diaphragms had less impact on the live load distribution factors than did any other variable investigated. For the exterior girders, the intermediate diaphragms slightly increased the live load distribution factor at low skew angles. At high skew angles ($\geq 30°$) the diaphragms were slightly beneficial. For the exterior and interior girders, the addition of end diaphragms decreased the distribution factors. This effect increased with increasing skew. For the exterior girders, the decrease ranged from 6% at no skew to almost 23% when the skew was 60°. When continuity was considered, the distribution factors for the exterior girder of the three-span model were less than 2% higher than those in the one-span model at low skew angles. An increase of up to 15% was observed when the skew was increased. Continuity decreased the live load distribution factors for the interior girder at low skew angles but increased for skews greater than 40°. The reason

for this behavior was unknown. Skew had little effect for an angle of 20°. At larger skew angles, the live load distribution factor decreased with increasing skew. In general, interior girders were more affected by skew than were exterior girders.

The results of a study by Cai et al. (26) showed that in cases with intermediate diaphragms, the increase of skew angle increases both the maximum strains and load distribution factors compared to a bridge with no skew angle. This effect is opposite to the case without intermediate diaphragms and implies that the interaction between skew angle and diaphragms is complicated and needs further consideration.

In an attempt to determine the effectiveness of intermediate diaphragms on live load distribution, Cheung et al. (34) investigated the effect of a parameter R that is defined as the total flexural stiffness of the diaphragms divided by the total transverse stiffness of the deck. An investigation on the effects of the number of diaphragms was also conducted. The α-θ method, used in the orthotropic plate theory, does not account for the presence of diaphragms but it was concluded that this method could be used in the design of slab-on-girder bridges provided that there are at least two or three intermediate diaphragms per span. Modifications were made to the equations for α and θ to account for diaphragms.

Culham and Ghali (35) showed that the presence of only one intermediate cross girder in the center of the span was more effective than adding more at several points along the span. In some cases two cross girders at the quarter points in addition to a cross girder in the center of the span improved load distribution and in other cases did not. Results from these cases showed small changes, thus the presence of one cross girder in the center was considered most effective.

Green et al. (54) showed that the presence of intermediate diaphragms reduced the maximum deflections by up to 17% for straight precast prestressed concrete bridges.

Eamon and Nowak (37) investigated the effects of barriers, sidewalks, and diaphragms on load distribution using the finite element method. It was shown that in the elastic range, secondary elements affect both the position of maximum girder moment and the moment magnitude and can result in a 10-40% decrease in girder distribution factor for typical cases. For the inelastic range, typical element stiffness combinations reduced the girder distribution factor by an additional 5-20%.

The distribution of live load for straight multiple steel box girder bridges was shown to be moderately affected by the presence of intermediate diaphragms in a study by Foinquinos et al. (45). Results showed that using only two cross frames suffice to redistribute the live load stresses up to 18%. Additional cross frames did not significantly improve the live load distribution. However, Sennah and Kennedy (111) concluded that the presence of at least three cross-bracing systems between support lines, with a maximum spacing of 7.5 m, significantly enhances the transverse load distribution of moments, forces, and deflections for composite multicell box girder bridges.

Kennedy and Grace (67) examined the influence of the number of diaphragms, aspect ratio, skew, and cracking of the concrete deck on the transverse load distribution in continuous composite bridges. Analytical results were generated using the orthotropic plate theory and verified by tests on two 1/8-scale bridge models. The results showed that the influence of diaphragms in the transverse distribution of the load becomes more significant for relatively wide bridges; moreover, this influence increases with increase in the skew angle. The presence steel I-beam diaphragms were shown to also enhance the

effectiveness of the orthotropic theory in predicting the elastic response of a continuous composite bridge. It was recommended that diaphragms in a skew composite bridge be place perpendicular to the flow of traffic. Transverse cracking of the concrete deck at the intermediate support did not significantly influence the transverse distribution of the longitudinal moment there. It also had little effect on the deflections as well as longitudinal and transverse moments at midspan of the continuous composite bridge.

Mabsout et al. (73) suggested introducing a 5% reduction factor for continuous bridges when using the distribution factor formulas developed from NCHRP Project 12-26 (138). It was shown that the AASHTO empirical distribution factor (S/5.5) overestimated the actual wheel load distribution by as much as 47% depending on the bridge geometry when considering continuous steel girder bridges. Therefore it was also suggested that an average reduction factor of 15% be adopted when applying the AASHTO empirical distribution factor.

In contradiction to their previous study, Mabsout et al. (74) stated that the formulas developed from the NCHRP Project 12-26 (141) could be used in analyzing and designing continuous as well as multilane bridges without introducing any correction or reduction factors. This study reinforced the AASHTO LRFD argument for not introducing adjustment factors to account for continuity in steel girder bridges.

Mabsout et al. (75) studied the influence of sidewalks and railings on wheel load distribution. It was shown that when these elements act integrally with the bridge deck, the outside girder is stiffened and attracts more load while reducing the load effects in the interior girders. Results showed that the contribution of bending moment from the concrete slab was about 4% when no sidewalk and/or railing were on the bridge. When a

sidewalk was introduced to either or both sides of the bridge, the concrete slab and sidewalk contributed to about 17% of the total bending moment of the exterior girder. The introduction of railing increased the contribution to about 45% and to about 52% for a combination of sidewalk and railing. The presence of these elements was shown to increase the load-carrying capacity of interior girders by a factor somewhere between 5-30%.

Modjeski and Masters, Inc. (81) conducted a research on shear correction in skewed multi-beam bridges under the NCHRP project 20-7/Task 107. Through finite element analysis of 41 bridge models, they studied the variation of the skew correction factor for live load shear along the length of exterior beams and across the beam supports or piers of simple-span as well as two-span continuous beam and slab bridges. The influence of skew angle, beam stiffness, span length, intermediate cross frames, beam spacing, slab thickness and bridge aspect ratio on the skew correction factor variation was also investigated. The study finding suggested that a reasonably approximation for the variation of the skew correction factor along the length of exterior girder in the studied bridge types was a linear distribution of the factor from its value at the obtuse corner of the bridge, determined according to the LRFD Specification, to a value of 1.0 at girder midspan. Similarly, the skew correction factor variation across the bearing lines of those bridges may be approximated by a linear distribution of the correction factor from its value at the obtuse corner of the bridge to a value of 1.0 at the acute corner of the bridge. The variations of the skew correction factors for shear in continuous bridges were identical to those proposed for simple span bridges.

Normandin and Massicotte (84) explained that the torsional stiffness of a steel box girder comes from three components: the St-Venant rigidity, the warping rigidity, and the distorsional rigidity. When the flexibility of any of these components is increased, the rigidity of the box girder diminishes. The analyses of single box girders indicated that adding only one diaphragm at midspan of a box girder magnified the torsional rigidity by up to fifteen times that of the same girder without a diaphragm.

Schilling (107) explained that the number of beams in a bridge is not an important parameter in actual bridges. For an infinitely stiff slab, the distribution factors depend greatly on the number of beams in the bridge because load is distributed to all beams. However, in an actual bridge, the ranges of slab and beam stiffnesses are such that the load is distributed primarily to only three or four beams.

Sengupta, and Breen (109) studied the effect of diaphragms in prestressed concrete girder and slab bridges. It was determined that the only significant role of interior diaphragms was to distribute load more evenly. No appreciable reduction in the governing design moment was found. A cost analysis showed that it would be more economical to increase girder strength than to rely on diaphragms to decrease the design moment. Interior diaphragms were shown to make the girders more vulnerable to damages from lateral impacts and were therefore recommend not to be provided in simply supported prestressed concrete girder and slab bridges. It was shown that the only significant role of end diaphragms was to support the free slab edge at the approach span.

Smith and Mikelsteins (118) explained that increased edge stiffening results in an increase in the bending moment carried by the exterior girder. Although the increased stiffness of the exterior girder will attract more of the total load, the resulting deflections

will be smaller. It was shown that for a bridge with a 15 m span subjected to an eccentric load, the average increase in exterior girder bending moments was 41, 27, and 104% for prestressed concrete girders, steel plate girders, and voided slab decks, respectively. Symmetric loading also caused increases in the bending moments for each bridge type. It was concluded that all types of edge stiffening significantly affect load distribution. Similar results were found by Sadler and Holowka (103) in a study on the effects of New Jersey barrier walls on cantilever slabs.

Soliman and Kennedy (119) studied the effects of bridge continuity, bridge aspect ratio, and intermediate steel I-beam diaphragms on the load distribution characteristics of slab-on-compact steel girder composite bridges at their ultimate limit state. Laboratory tests were conducted on four composite bridge models, two with simply supported single spans and the other two with continuous two spans. A few of the conclusions from this study are as follows: 1) the bridge aspect ratio has a significant influence on the load distribution factors at the ultimate load; 2) the load distribution factors at service and ultimate loads for continuous two-span bridges are not significantly different from those for simple-span bridges; 3) the degree of eccentricity of load from the longitudinal center line of the bridge influences the differences in the girder load distribution factors; and 4) there is an optimum number of welded diaphragms for improving the load distribution characteristics of a bridge beyond which no improvement should be expected.

The results from a field test, conducted by Stallings et al. (121), to determine the effect of diaphragm removal, showed that intermediate diaphragms have only a small effect on the transverse distribution of truck loads. Moore et al. (80) also concluded that cross-frames did not cause load distribution to vary significantly, which suggested that

the load is primarily distributed through the bridge deck for bridges without skewed supports. Likewise, Ramaiah et al. (101) concluded that intermediate diaphragms do not have noticeable effect on the behavior of a box girder structure or the redistribution of loads.

Modeling

8. Aswad, A., and Chen, Y., "Impact of LRFD Specifications on Load Distribution of Prestressed Concrete Girders," PCI Journal, Vol. 39, No. 5 (1994), pp. 78-89.

18. Bakht, B., Jaeger, L.G., Cheung, M.S., and Mufti, A.A., "The State of the Art in Analysis of Cellular and Voided Slab Bridges," Canadian Journal of Civil Engineering, Vol. 8, No. 3 (September 1981), pp. 376-391.

21. Barr, P.J., Eberhard, M.O., and Stanton, J.F., "Live-Load Distribution Factors in Prestressed Concrete Girder Bridges," Journal of Bridge Engineering, Vol. 6, No. 5 (September/October 2001), pp. 298-306.

26. Cai, C.S., Shahawy, M., and Peterman, R.J., "Effect of Diaphragms on Load Distribution of Prestressed Concrete Bridges," Transportation Research Record, No. 1814, Transportation Research Board, Washington, D.C. (2002), pp. 47-54.

28. Chen, Y., "Distribution of Vehicular Load on Bridge Girders by the FEA using ADINA: Modeling, Simulation, and Comparison," Computer & Structures, Vol. 72, No 1-3 (July/August 1999), pp 127-139.

30. Chen, Y., "Refined and Simplified Methods of Lateral Load Distribution for Bridges with Unequally Spaced Girders: I. Theory," Computers and Structures, Vol. 55, No. 1 (April 1995), pp. 1-15.

61. Imbsen, R.A., and Nutt, R.V., “Load Distribution Study on Highway Bridges Using STRUDL Finite Element Analysis Capabilities,” Conference On Computing in Civil Engineering: Proceedings (1978), pp. 639-655.

75. Mabsout, M.E., Tarhini, K.M., Frederick, G.R., and Kobrosly, M., “Influence of Sidewalks and Railings on Wheel Load Distribution in Steel Girder Bridges,” Journal of Bridge Engineering, Vol. 2, No. 3 (August 1997), pp. 88-96.

76. Mabsout, M.E., Tarhini, K.M., Frederick, G.R., and Tayar, C., “Finite-Element Analysis of Steel Girder Highway Bridges,” Journal of Bridge Engineering, Vol. 2, No. 3 (August 1997), pp. 83-87.

84. Normandin, P., and Massicotte, B., “Load Distribution in Composite Steel Box Girder Bridges,” Developments in Short and Medium Span Bridge Engineering (1994), pp. 165-176.

101. Ramaiah, S.R., Seyedmadani, N.A., and Oliden, O.A., “Finite Element Modeling, Analysis, and Design of Highly Skewed Post-Tensioned Concrete Bridges,” Transportation Research Record No. 1290, Transportation Research Board, Washington D.C. (1991), pp.144-151.

112. Shahawy, M., and Huang, D., “Analytical and Field Investigation of Lateral Load Distribution in Concrete Slab-On-Girder Bridges,” ACI Structural Journal, Vol. 98, No. 4 (July/August 2001), pp. 590-599.

120. Song, S.T., Chai, Y.H., and Hida, S.E., “Live Load Distribution in Multi-Cell Box-Girder Bridges and its Comparison with the AASHTO LRFD Bridge Design

Specifications," University of California, Davis, California, Final Report to Caltrans No. 59A0148 (July 2001).

134. Wipf, T.J., Klaiber, W., and Funke, R.W., "Longitudinal Glued Laminated Timber Bridge Modeling," Journal of Structural Engineering, Vol. 116, No. 4 (April 1990), pp. 1121-1134.

In the study by Aswad and Chen (8), the bridge deck structural system was modeled using both shell and beam (stiffener) elements. A standard quadrilateral shell element of constant thickness was incorporated in modeling the horizontal slab. The stiffeners were described using a standard isoparametric beam element. Rigid links were used to connect the centers of the slab and beam, which allowed for composite action. The computation of the composite beam moment as well as quality control checks of a finite element program were also discussed.

Bakht et al. (18) summarized the results of an extensive literature search and initial review of the available methods of analyzing cellular and voided slab bridges. The following methods have been used for several years: 1) orthotropic plate methods; 2) sandwich plate methods; 3) frame and grillage methods; 4) finite element methods; 5) finite strip methods; and 6) folded plate methods. The grillage method appeared to be the most versatile and efficient method that can realistically model the transverse cell distortion of cellular and voided structures. For a two-dimensional idealization of a structure, the equivalent plate parameters should model the actual structure as closely as possible without their requiring complex calculations. The equations for calculating the various equivalent plate parameters were also presented and were said to be the most appropriate of all methods.

Barr et al. (21) chose to use a fine element mesh in the deck for their finite element model. This was done in order for the nodes to be near the truck wheels. A node spacing of approximately 2 ft transversely, to fit the 8 ft girder spacing, and 1 ft longitudinally was used. The arrangement of nodes and elements offered the following features: 1) the vertical location of the deck, lift, and girder elements reflected accurately the locations of those members in the bridge; 2) the flexural and torsional properties of the precast girders could be lumped in the frame elements that were placed at the center of gravity of the girders; 3) bending moments in the composite girders could be extracted from the output easily; and 4) the number of nodes was small enough to offer a tractable solution. Both the intermediate diaphragms and the pier diaphragms were modeled using shell elements. The pier diaphragms were made to act compositely with the pier caps by using rigid constraints. The finite element model also included columns and a pier cap beam at the intermediate piers. The columns and pier cap beams were modeled with 1 ft long frame elements. At each abutment, elastomeric bearings in the bridge were represented in the analytical model by releasing the horizontal displacements.

Chen (28, 30) explained that shell elements should be proportioned so that the maximum aspect ratio (element length/element width) always remains less than two to one. In his study, efforts were made to see how many elements are needed for accuracy and efficiency. As a result, it was recommended that two transverse slab elements between two adjacent girders and 12 divisions along the bridge span be used for bridges with a girder spacing of 6-12 ft and span length of 50-150 ft. Similarly, Ramaiah et al. (101) used an aspect ratio of 1 in critical areas and of 2 in non-critical areas in order to increase the accuracy of the results in the finite element analysis.

Mabsout et al. (76) compared the performance of four finite element modeling techniques used in evaluating the wheel load distribution factors of steel girder bridges. SAP90 and ICES-STRUDL were the two finite element programs used to perform the analysis. The results of all modeling techniques were compared with AASHTO wheel load distribution factors and published experimental results. The first finite element model (case a) modeled the concrete slab as quadrilateral shell elements with five degrees of freedom at each node and the steel girders as space frame members with six degrees of freedom. The centroid of each girder coincided with the centroid of the concrete slab. The second finite element model (case b) idealized the concrete slab as quadrilateral shell elements and girders as eccentrically connected space frame members as in case a, but rigid links were added to accommodate for the eccentricity of the girders. The third finite element model (case c) idealized the concrete slab and girder webs as quadrilateral shell elements and girder flanges as space frame elements, and flange to deck eccentricity was modeled by imposing a rigid link. The fourth finite element model (case d) idealized the concrete slab using isotropic eight node brick elements with three degrees of freedom at each node and the steel girder flanges and webs using quadrilateral shell elements. Hinges and rollers were used in all bridges for supports. The maximum experimental wheel load distribution factors for seven bridges were compared with NCHRP 12-26 and the AASHTO Standard distribution factors. This study supported previous findings of the AASHTO Standard methods yielding highly conservative distribution factors for longer span lengths and girder spacing. The NCHRP 12-26 methods, while still conservative for most cases, correlated well with field test data and with the modeling

techniques used in case a and d. Mabsout (75) used the same techniques as described above to determine the influence of sidewalks and railings on wheel load distribution.

Normandin and Massicotte (84) used a quadrilateral plate-shell element to represent the steel plates and the concrete slab. A minimum of two elements was used vertically for the webs, the bottom flanges, and the deck between webs. The aspect ratio of the plate element never exceeded 1.5. The top flanges, bracing, and diaphragms were modeled with beam elements. Rigid link elements were used to connect the top flange to the centroid of the slab to obtain the appropriate eccentricity. The modeling was performed with the finite element program SAP90.

Shahawy and Huang (112) used a series of quadrilateral plate and shell elements with six degrees of freedom at each node to model the bridge deck between girders. The girders, diaphragms, and the part of the deck over the beam flanges were modeled using space bar elements. The centroid of the beam was connected to the centroid of the slab by using rigid links. Similarly, Imbsen and Nutt (61) used plate bending and membrane finite elements to model the deck slab and eccentrically connected space frame members to model the girders and bracing. When comparing finite element results to field-testing, Cai et al. (26), concluded that better results can be predicted when modeling diaphragms noncomposite with the slab.

Song et al. (120) used SAP2000 to perform the analysis of box girder bridges using both the grillage method and the finite element method. For the grillage model, the longitudinal elements for the interior and exterior girders were assumed to be located at the intersection of the centerline of the web and the centroidal axis of the box girder cross section. The transverse elements were assumed to be located on the same plane as the

longitudinal elements. Each longitudinal girder was divided into ten beam-column elements per span. The nodes at the continuous support were restrained against translation in all three directions, whereas the nodes at the two ends were restrained against translation in the vertical and transverse directions. No rotational restraints were imposed at the continuous or end supports. For the finite element model, two shell elements for each web, for the top and bottom flange between webs, and for each diaphragm at the continuous or end supports were used. In the longitudinal direction, the girders were discretized into ten elements per span. The finite element model predicted a slightly smaller deflection than the grillage model, however, the difference in deflections for the two models was generally less than 5%.

Wipf et al. (134) used the finite element program SAP IV to model a glued, laminated, longitudinal-deck highway bridge. The glued laminated panels of the longitudinal bridge were modeled as thin plate/shell elements. These elements had five degrees of freedom per node. Stiffener beams were modeled using a three-dimensional beam element. Beam elements were also selected to model the connections. These elements were assigned a very small flexural and torsional stiffness. Rigid links that consisted of three-dimensional beam elements with very large flexural, axial, and torsional stiffnesses were used to simulate the load application of the connections.

Field Testing

4. Amer, A., Arockiasamy, M., and Shahawy, M., "Load Distribution of Existing Solid Slab Bridges Based on Field Tests," Journal of Bridge Engineering, Vol. 4, No. 3 (August 1999), pp. 189-193.

7. Arockiasamy, M., and Amer, A., “Load Distribution on Highway Bridges Based on Field Test Data,” Final Report, Florida DOT HPR Study No. 0668, WPI 0510668, Job No. 99500-3512-119, Center for Infrastructure and Constructed Facilities, Florida Atlantic University, Boca Raton, Florida (1995).

19. Barker, M.G., “Quantifying Field-Test Behavior for Rating Steel Girder Bridges,” Journal of Bridge Engineering, Vol. 6, No. 4 (July/August 2001), pp. 254-261.

22. Bell, N.B., “Load Distribution of Continuous Bridges Using Field Data and Finite Element Analysis,” M.S. Thesis, Florida Atlantic University (1998).

43. Eom, J., and Nowak, A.S., “Live Load Distribution for Steel Girder Bridges,” Journal of Bridge Engineering, Vol. 6, No. 6 (November/December 2001), pp. 489-497.

47. Fu, C.C., Elhelbawey, M., Sahin, M.S., and Schelling, D.R., “Lateral Distribution Factor from Bridge Field Testing,” Journal of Structural Engineering, Vol. 122, No. 9 (September 1996), pp. 1106-1109.

58. Huo, X.S., Crouch, L.K., Ung, F., Zhu, P., and Goodwin, W.A., “Experimental Study of Optimal Erection Schedule of Prestressed Concrete Bridge Girders,” Final Report, Tennessee DOT Project No. TNSPR-RES 1188, Tennessee Technological University, Cookeville, TN (December 2002).

69. Kim, S.J., and Nowak, A.S., “Load Distribution and Impact Factors for I-Girder Bridges,” Journal of Bridge Engineering, Vol. 2, No. 3 (August 1997), pp. 97-104.

88. Nowak, A.S., Eom, J. Sanli, A., and Till, R., "Verification of Girder-Distribution Factors for Short-Span Steel Girder Bridges by Field Testing," Transportation Research Record No. 1688, Transportation Research Board, Washington, D.C. (1999), pp. 62-67.

107. Schilling, C.H., "Lateral Distribution Factors for Fatigue Design," Journal of the Structural Division, Vol. 108, No. ST9 (September 1982), pp. 2015-2033.

108. Schwarz, M., and Laman, J.A., "Response of Prestressed Concrete I-Girder Bridge to Live Load," Journal of Bridge Engineering, Vol. 6, No. 1 (January/February 2001), pp. 1-8.

112. Shahawy, M., and Huang, D., "Analytical and Field Investigation of Lateral Load Distribution in Concrete Slab-On-Girder Bridges," ACI Structural Journal, Vol. 98, No. 4 (July/August 2001), pp. 590-599.

131. Tiedeman, J.L., Albrecht, P., and Cayes, L., "Behavior of Two-Span Continuous Bridge Under Truck Axle Loading," Journal of Structural Engineering, Vol. 119, No. 4 (April 1993), pp. 1234-1250.

Amer et al. (4) conducted field tests to determine the equivalent width for solid slab bridges. Based on the field tests it was shown that both the AASHTO Standard and AASHTO LRFD codes result in equivalent widths that are lower, which means more conservative. It was also shown that a bridge behaves nonlinearly when longitudinal cracks are present, thus a more accurate nonlinear analysis would be required to determine the equivalent width. In the full report by Arockiasamy and Amer (7), in

addition to solid slab bridges, the results of field-test on slab-on-AASHTO girder bridges and double tee beam bridges were discussed.

Barker (19) selected the Missouri State Bridge R289 to demonstrate the field-testing capacity rating procedures. The bridge had multiple continuous spans, positive moment region composite and noncomposite sections, negative moment region noncomposite sections, rocker bearings, and substantial curbs and railings. It was shown that the stresses differ from the analytical stresses due to the effects of: 1) actual impact factor; 2) actual section dimensions; 3) unaccounted system stiffness such as curbs and railings; 4) actual lateral live load distribution; 5) bearing restraint effects; 6) actual longitudinal live load distribution; and 7) unintended or additional composite action. It is important for these factors that tend to increase the load capacity be separated and quantified to remove the unwanted contributions and confirm the origin of the usable benefit.

Bell (22) conducted load testing on skew slab-on-girder and continuous skew slab-on-steel girder bridges. A finite element model was used to analyze the test bridges. In general, the calculated deflections were about 24% higher than the measured values for the skew slab-on-girder bridge. However, the measured and calculated strains showed better agreement, which indicated that the finite element model used in the analysis was more accurate in predicting the strains. Load distribution factors based on measured and calculated strains were smaller than those based on AASHTO Standard Specifications (5) and AASHTO LRFD Specifications (6). The difference between the measured and computed maximum strains at midspan of the continuous skew slab-on-steel girder bridge was in the range of 11% when diaphragms were not considered in the finite

element analysis. However, the difference was only 3% when diaphragms were taken into account in the finite element analysis.

Eom and Nowak (43) performed a field study on live load distribution factors, in which strains were measured for 17 steel I-girder bridges in Michigan, with spans from 10 to 45 m and two lanes of traffic. Measurements were taken under passages of one and two vehicles, each being a Michigan three-unit, 11-axle truck with known weight and axle configuration. For each tested bridge, the trucks were driven at very low speeds to simulate static loads and at regular speed to obtain dynamic effects on the bridge. The test results were used to calculate the distribution factors and to calibrate the 3D ABAQUS finite element program models. It was found that for bridges with ideal simple supports (roller-hinge), code-specified distribution factors for one lane loading were more realistic. Also, the absolute value of measured strains were lower than that predicted by analysis. One of the most important reasons was the partial fixity of the supports. For one lane of loading, both codes (AASHTO and LRFD) were conservative. Additionally, for short span girder bridges, the AASHTO Standard GDF values and the AASHTO LRFD are not excessively permissive and the LRFD methods provide distribution factors closer to the measured values. It was stated that the discrepancy between the code-specified and test values indicates that the actual bridge conditions can be different than what is assumed in the code. The different conditions could be caused by deterioration.

The research by Fu et al. (47) yielded wheel load distribution factors based on strain data collected from four in-service steel I-girder bridges in the state of Maryland. It was determined that distribution factors were dependent on transverse loading position and independent of load configuration or truck weight. Also, it was observed that for

skewed bridges, strains along transverse lines were not equal. From the field-testing of the four bridge structures under real truck loading, the strain data were collected and used in evaluation of live load distribution factors. The obtained strains were also compared with those calculated from different methods. All the code methods including the AASHTO Standard, the AASHTO LRFD, and the Ontario Highway Bridge Design Code produced higher distribution factors.

A live load test on the Pistol Creek Bridge in Blount County, Tennessee was conducted by Huo et al. (58). The bridge is a twin-bridge on State Route 162 with five spans and five lines of AASHTO Type III prestressed concrete beams spaced at 3.23 m center to center. The total length of the bridge is 113.75 m and the width is 15.61 m. The thickness of the cast-in-place concrete deck is 222 mm. The interior beams in the first and second spans of both bridges were instrumented to monitor the time-dependent behavior of the prestressed girders. Two TDOT three-axle dump trucks were used in the live load test. Both bridges were tested with one-truck and two-truck loadings. During the test, trucks moved along the designated loading lines on bridges in a slow speed, and then stopped and stayed at four locations (0.4 span length, end, quarter span length, and midspan) for at least five minutes to allow the data acquisition system to record adequate data. The measured data included temperature and strains at the four instrumented sections and deflections at midspan sections. The moment of the interior beams was determined using the measured strain. The corresponding moment distribution factor was then calculated by dividing the obtained moment from the live load test by the moment obtained in a simple beam analysis. The test results showed that the distribution factors obtained in the second span were very close to the ones from Henry's method (less than

1%) and finite element analysis (2%), but slightly smaller than the AASHTO LRFD method (8%) and much smaller than the AASHTO Standard method (23%). The obtained distribution factors in the first span were much smaller than the values from any other method (28% - 68%). This could be because the actual bridge bent condition was much more rigid than the assumed support condition in the analysis.

In a field study of two simply supported steel I-girder bridges conducted by Kim and Nowak (69), more proof of the inaccuracy and unreliability of the AASHTO Standard and the AASHTO LRFD were revealed. For both bridges, strains were measured under normal truck traffic to investigate statistical characteristics of girder distribution factors (GDF's). GDF's obtained for bridge one were more uniform for each girder than for bridge two even with more sparsely spaced girders. The distribution factors for bridge one were also much smaller than the code specifications. For two-lane loading, compared to the measured maximum factors, the AASHTO Standard and the AASHTO LRFD methods result in larger values (16% and 28%, respectively). On the other hand, bridge two distribution factors from the LRFD methods were lower than the AASHTO Standard methods, and both were substantially higher (Standard = 24% and LRFD = 19%) than experimental results.

Nowak et al. (88) tested five noncomposite steel girder bridges in Michigan. All bridges had two traffic lanes and were simply supported. The spans measured 10-18 m and the girders were spaced at about 1.5 m. The distribution factors determined from the field measurements were lower than those calculated by the AASHTO Standard Specifications (5) and the AASHTO LRFD Specifications (6). Results indicated that the

code-specified distribution factors are adequate for bridges with both a short span and girder spacing.

Schilling (107) conducted an extensive finite element parametric study to develop a chart giving lateral distribution factors for the fatigue design of steel girder highway bridges. Field measurements were taken from twenty-one steel bridges in order to determine lateral distribution factors. The factors were in good agreement with the developed chart, but were generally much less than the AASHTO factors.

Schwarz and Laman (108) conducted field tests on three prestressed concrete I-girder bridges to obtain dynamic load allowance statistics, girder distribution factors, and service level stress statistics. The field-based data were compared to approximate (AASHTO Standard and AASHTO LRFD Specifications) and numerical model (grillage method) results. The approximate results were greater than the measured results for both one- and two-design lanes. The results from the grillage model for transverse load distribution were in close agreement to those from the measured results. It was stated that neglecting the diaphragms in the grillage model might improve the accuracy of the results, particularly for shorter span bridges.

Shahawy and Huang (112) conducted several field tests to verify the accuracy of the proposed modified load distribution factor equation. Seven bridge tests were chosen and the results were compared to theoretical results. It was shown that the test results were very close to those obtained by the finite element analysis, which in turn was close to the proposed modification to the load distribution factor equation specified in the AASHTO LRFD Specifications (6).

The inaccuracy and inconsistency of the AASHTO Standard Specifications (5) and NCHRP 12-26 methods (141) was further demonstrated in a study by Tiedeman et al. (131). Measured reactions and moments were compared with those calculated by finite element methods, AASHTO analysis, and NCHRP 12-26 equations. For shear, the reactions calculated with finite element analysis varied from 90% (for interior girder) to 108% (for exterior girder) of experimental values. This was possibly due to the high torsional stiffness of the exterior girders, which could not distort out of plane relative to the deck in the finite element model, but could partially do so in the test bridge. The finite element stresses correlated within an average of 3% with the measured stresses. The AASHTO Standard method only led to good predictions of the exterior girder reactions for two and three lanes of loading and the interior girder reactions for two lanes of loading. When the load was applied near the interior girder, the AASHTO method poorly predicted all reactions. Exterior girder reactions were very unconservative, and those for the interior girder were very conservative, the results became worse as fewer lanes were loaded. The stresses predicted by the AASHTO analysis were typically higher than the measured stresses. The stresses in the exterior girders varied from 98-125% of experimental values. The interior girders, however, varied from 132-308% of experimental stresses. The NCHRP 12-26 method was also highly conservative for single lane loading for interior girders (241% and 257%) and slightly conservative for multiple-lane loading (131% and 128 %), including the 0.9 reduction factor. Stresses for all other loading cases were greatly over predicted (207-464% of measured results).

Nonlinear Finite Element Analysis

3. Al-Mahaidi, R. Taplin, G. and Giufre, A., "Load Distribution and Shear Strength Evaluation of an Old Concrete T-Beam Bridge," Transportation Research Record No. 1696, Transportation Research Board, Washington, D.C. (2000), pp. 52-62.

44. Evans, H.R., "Simplified Methods for the Analysis and Design of Bridges of Cellular Cross-Section," Analysis and Design of Bridges (Proceedings of the NATO Advanced Study Institute), No. 74 (1984), pp. 95-115.

48. Fu, K-C., and Lu, F., "Nonlinear Finite-Element Analysis for Highway Bridge Superstructures," Journal of Bridge Engineering, Vol. 8, No. 3 (May/June 2003), pp. 173-179.

119. Soliman, M., and Kennedy, J.B., "Load Distribution in Composite Bridges at the Ultimate Limit State," Developments in Short and Medium Span Bridge Engineering, Vol. 1 (1990), pp. 201-214.

Al-Mahaidi et al. (3) conducted a nonlinear finite element study of a reinforced concrete T-beam bridge. Nonlinear finite element analysis was chosen in order to determine the ultimate load capacity. The nonlinear finite element model accurately predicted the ultimate strength when compared to the measured ultimate load.

Soliman and Kennedy (119) stated that to correctly assess the ultimate load-carrying capacity of a bridge it is imperative that the nonlinear load-deformation response of a bridge be considered up to the failure load. An incremental grillage approach was discussed by Evans (44), which allowed for the prediction of the nonlinear and collapse behavior of cellular structures.

Fu and Lu (48) used a nonlinear finite element method to model the concrete deck of a slab-on-steel girder composite bridge. He explained that under working load conditions the steel girders behave elastically, but the concrete deck cannot be adequately represented by a linearly elastic model because concrete is a nonlinear material with very small tensile strength. When comparing deflections from the transformed section method, nonlinear finite element method, and experimental method it was shown that the nonlinear finite element model compared very well with experimental results, while the transformed section method greatly under-predicted the deflections.

Bridge Type

Steel I-Beam

7. Arockiasamy, M., and Amer, A., "Load Distribution on Highway Bridges Based on Field Test Data," Final Report, Florida DOT HPR Study No. 0668, WPI 0510668, Job No. 99500-3512-119, Center for Infrastructure and Constructed Facilities, Florida Atlantic University, Boca Raton, Florida (1995).

10. Azizinamini, A., Kathol, S., and Beacham, M.W., "Influence of Cross Frames on Load Resisting Capacity of Steel Girder Bridges," Engineering Journal, Vol. 32, No. 3 (Third Quarter 1995), pp. 107-116.

16. Bakht, B., Cheung, M.S., and Aziz, T.S., "Application of a simplified method of calculating longitudinal moments to the Ontario highway bridge design code," Canadian Journal of Civil Engineering, Vol. 6, No. 1 (March 1979), pp. 36-50.

19. Barker, M.G., "Quantifying Field-Test Behavior for Rating Steel Girder Bridges," Journal of Bridge Engineering, Vol. 6, No. 4 (July/August 2001), pp. 254-261.

22. Bell, N.B., “Load Distribution of Continuous Bridges Using Field Data and Finite Element Analysis,” M.S. Thesis, Florida Atlantic University (1998).

24. Bishara, A.G., Liu, M.C., and El-Ali, N.D., “Wheel Load Distribution on Simply Supported Skew I-Beam Composite Bridges,” Journal of Structural Engineering, Vol. 119, No. 2 (February 1993), pp. 399-419.

25. Burdette, E.G., and Goodpasture, D.W., “Correlation of Bridge Load Capacity Estimates with Test Data,” National Cooperative Highway Research Program Report 306, Transportation Research Board, Washington, D.C. (1988).

33. Cheung, M.S., Gardner, N.J., and Ng, S.F., “Ultimate Load Distribution Characteristics of a Model Slab-on-Girder Bridges,” Canadian Journal of Civil Engineering, Vol. 14, No. 6 (December 1987), pp. 739-752.

34. Cheung, M.S., Jategaonkar, R., and Jaeger, L.G., “Effects of Intermediate Diaphragms in Distributing Live Loads in Beam-and-Slab Bridges,” Canadian Journal of Civil Engineering, Vol. 13, No. 8 (September 1986), pp. 278-292.

37. Eamon, C.D., and Nowak, A.S., “Effects of Edge-Stiffening Elements and Diaphragms on Bridge Resistance and Load Distribution,” Journal of Bridge Engineering, Vol. 7, No. 5 (September/October 2002), pp. 258-266.

38. Ebeido, T., and Kennedy, J.B., “Girder Moments in Continuous Skew Composite Bridges,” Journal of Bridge Engineering, Vol. 1, No. 1 (February 1996), pp. 37-45.

39. Ebeido, T., and Kennedy, J.B., “Shear and Reaction Distributions in Continuous Skew Composite Bridges,” Journal of Bridge Engineering, Vol. 1, No. 4 (November 1996), pp. 155-165.

40. Ebeido, T., and Kennedy, J.B., “Shear Distribution in Simply Supported Skew Composite Bridges,” Canadian Journal of Civil Engineering, Vol. 22, No. 6 (December 1995), pp. 1143-1154.

42. Elhanhal, M.K., Albrecht, P., and Cayes, L.R., “Load Distribution in a Two-Span Continuous Bridge,” Report No. FHWA-RD-89-101, Federal Hwy. Administration, McLean, VA. (1989).

43. Eom, J., and Nowak, A.S., “Live Load Distribution for Steel Girder Bridges,” Journal of Bridge Engineering, Vol. 6, No. 6 (November/December 2001), pp. 489-497.

48. Fu, K-C., and Lu, F., “Nonlinear Finite-Element Analysis for Highway Bridge Superstructures,” Journal of Bridge Engineering, Vol. 8, No. 3 (May/June 2003), pp. 173-179.

49. Galambos, T.V., Leon, R.T., French, C.W., Barker, M., and Dishongh, B., “Inelastic Rating Procedures for Steel Beam and Girder Bridges,” National Cooperative Highway Research Program Report 352, Transportation Research Board, Washington, D.C. (1993).

52. Goodrich, B.L., and Puckett, J.A., “Simplified Load Distribution for Vehicles with Nonstandard Axle Gages,” Transportation Research Record No. 1696, Vol. 2, Transportation Research Board, Washington, D.C. (April, 1999), pp. 158-170.

55. Hays, C., Sessions, L., and Berry, A., “Further Studies on Lateral Load Distribution Using a Finite Element Method,” Transportation Research Record No. 1072, Transportation Research Board, Washington, D.C. (1986), pp. 6-14.

60. Huo, X.S., Wasserman, P.E., Zhu, P., “A Simplified Method of Lateral Distribution of Live Load Moment,” Journal of Bridge Engineering (2002) (n press).

61. Imbsen, R.A., and Nutt, R.V., “Load Distribution Study on Highway Bridges Using STRUDL Finite Element Analysis Capabilities,” Conference On Computing in Civil Engineering: Proceedings (1978), pp. 639-655.

67. Kennedy, J.B., and Grace, N.F., “Load Distribution in Continuous Composite Bridges,” Canadian Journal of Civil Engineering, Vol. 10, No. 3 (September 1983), pp. 384-395.

69. Kim, S.J., and Nowak, A.S., “Load Distribution and Impact Factors for I-Girder Bridges,” Journal of Bridge Engineering, Vol. 2, No. 3 (August 1997), pp. 97-104.

71. Kuzmanovic, B.O., and Sanchez, M.R., “Lateral Distribution of Live Loads on Highway Bridges,” Journal of Structural Engineering, Vol. 112, No. 8 (August 1986), pp. 1847-1862.

73. Mabsout, M.E., Tarhini, K.M., Frederick, G.R., and Kesserwan, A., “Effect of Continuity on Wheel Load Distribution in Steel Girder Bridges,” Journal of Bridge Engineering, Vol. 3, No. 3 (August 1998), pp. 103-110.

74. Mabsout, M.E., Tarhini, K.M., Frederick, G.R., and Kesserwan, A., “Effect of Multilanes on Wheel Load Distribution in Steel Girder Bridges,” Journal of Bridge Engineering, Vol. 4, No. 2 (May 1999), pp. 99-106.

75. Mabsout, M.E., Tarhini, K.M., Frederick, G.R., and Kobrosly, M., “Influence of Sidewalks and Railings on Wheel Load Distribution in Steel Girder Bridges,” Journal of Bridge Engineering, Vol. 2, No. 3 (August 1997), pp. 88-96.

76. Mabsout, M.E., Tarhini, K.M., Frederick, G.R., and Tayar, C., “Finite-Element Analysis of Steel Girder Highway Bridges,” Journal of Bridge Engineering, Vol. 2, No. 3 (August 1997), pp. 83-87.

80. Moore, M., Strand, K.A., Grubb, M.A., and Cayes, L.R., “Wheel-Load Distribution Results from AISI-FHWA Model Bridge Study,” Transportation Research Record No. 1275, Transportation Research Board, Washington, D.C. (1990), pp. 34-44.

88. Nowak, A.S., Eom, J. Sanli, A., and Till, R., “Verification of Girder-Distribution Factors for Short-Span Steel Girder Bridges by Field Testing,” Transportation Research Record No. 1688, Transportation Research Board, Washington, D.C. (1999), pp. 62-67.

106. Sanders, W.W., Jr., and Elleby, H.A., “Distribution of Wheel Loads on Highway Bridges,” National Cooperative Highway Research Program Report No. 83, Transportation Research Board, Washington, D.C. (1970).

107. Schilling, C.H., “Lateral Distribution Factors for Fatigue Design,” Journal of the Structural Division, Vol. 108, No. ST9 (September 1982), pp. 2015-2033.

112. Shahawy, M., and Huang, D., “Analytical and Field Investigation of Lateral Load Distribution in Concrete Slab-On-Girder Bridges,” ACI Structural Journal, Vol. 98, No. 4 (July/August 2001), pp. 590-599.

118. Smith, K.N., and Mikelsteins, I., “Load Distribution in Edge Stiffened Slab and Slab-on-Girder Bridge Decks,” Canadian Journal of Civil Engineering, Vol. 15, No. 6 (December 1988), pp. 977-983.

119. Soliman, M., and Kennedy, J.B., “Load Distribution in Composite Bridges at the Ultimate Limit State,” Developments in Short and Medium Span Bridge Engineering, Vol. 1 (1990), pp. 201-214.

121. Stallings, J.M., Cousins, T.E., and Stafford, T.E., “Removal of Diaphragms from Three-Span Steel Girder Bridge,” Journal of Bridge Engineering, Vol. 4, No. 1 (February 1999), pp. 63-70.

125. Tabsh, S.W., and Tabatabai, M., “Live Load Distribution in Girder Bridges Subject to Oversized Trucks,” Journal of Bridge Engineering, Vol. 6, No. 1 (January/February 2001), pp. 9-16.

127. Tarhini, K.M., and Frederick, G.R., “Wheel Load Distribution in I-Girder Highway Bridges,” Journal of Structural Engineering, Vol. 118, No. 5 (May 1992), pp. 1285-1295.

131. Tiedeman, J.L., Albrecht, P., and Cayes, L., “Behavior of Two-Span Continuous Bridge Under Truck Axle Loading,” Journal of Structural Engineering, Vol. 119, No. 4 (April 1993), pp. 1234-1250.

132. Tobias, D.H., Anderson, R.E., Khayyat, S.K., Uzman, Z.B., and Riechers, K.L., "Simplified AASHTO LRFD Girder Live Load Distribution in Illinois," Journal of Bridge Engineering (in press).

Closed Steel or Precast Concrete Boxes

8. Aswad, A., and Chen, Y., "Impact of LRFD Specifications on Load Distribution of Prestressed Concrete Girders," PCI Journal, Vol. 39, No. 5 (1994), pp. 78-89.

16. Bakht, B., Cheung, M.S., and Aziz, T.S., "Application of a simplified method of calculating longitudinal moments to the Ontario highway bridge design code," Canadian Journal of Civil Engineering, Vol. 6, No. 1 (March 1979), pp. 36-50.

32. Chen, Y., and Aswad, A., "Stretching Span Capability of Prestressed Concrete Bridges Under AASHTO LRFD," Journal of Bridge Engineering, Vol. 1, No. 3 (August 1996), pp. 112-120.

36. Davis, R.E., Bon, V.D., and Semans, F.M., "Live Load Distribution in Concrete Box-Girder Bridges," Transportation Research Record, No. 871, Transportation Research Board, Washington, D.C. (1982), pp. 47-52.

60. Huo, X.S., Wasserman, P.E., Zhu, P., "A Simplified Method of Lateral Distribution of Live Load Moment," Journal of Bridge Engineering (2002) (in press).

71. Kuzmanovic, B.O., and Sanchez, M.R., "Lateral Distribution of Live Loads on Highway Bridges," Journal of Structural Engineering, Vol. 112, No. 8 (August 1986), pp. 1847-1862.

89. Oesterle, R.G., Glikin, J.D., and Larson, S.C., "Design of Precast Prestressed Bridge Girders Made Continuous," National Cooperative Highway Research Program Report 322, Transportation Research Board, Washington, D.C. (1989).

101. Ramaiah, S.R., Seyedmadani, N.A., and Oliden, O.A., "Finite Element Modeling, Analysis, and Design of Highly Skewed Post-Tensioned Concrete Bridges," Transportation Research Record No. 1290, Transportation Research Board, Washington D.C. (1991), pp.144-151.

106. Sanders, W.W., Jr., and Elleby, H.A., "Distribution of Wheel Loads on Highway Bridges," National Cooperative Highway Research Program Report No. 83, Transportation Research Board, Washington, D.C. (1970).

110. Sennah, K.M., and Kennedy, J.B., "Literature Review in Analysis of Box-Girder Bridges," Journal of Bridge Engineering, Vol. 7, No. 2 (March/April 2002), pp. 134-143.

120. Song, S.T., Chai, Y.H., and Hida, S.E., "Live Load Distribution in Multi-Cell Box-Girder Bridges and its Comparison with the AASHTO LRFD Bridge Design Specifications," University of California, Davis, California, Final Report to Caltrans No. 59A0148 (July 2001).

Open Steel or Precast Concrete Boxes

16. Bakht, B., Cheung, M.S., and Aziz, T.S., "Application of a simplified method of calculating longitudinal moments to the Ontario highway bridge design code," Canadian Journal of Civil Engineering, Vol. 6, No. 1 (March 1979), pp. 36-50.

45. Foinquinos, R., Kuzmanovic, B., and Vargas, L.M., “Influence of Diaphragms on Live Load Distribution in Straight Multiple Steel Box Girder Bridges,” Proc., 15th Structures Congress, Portland, OR, Vol. 1 (April 1997), pp. 89-93.

57. Heins, C.P., “Box Girder Bridge Design State-of-the-Art,” Engineering Journal of the American Institute of Steel Construction, Vol. 15, No. 4 (May 1978), pp. 126-142.

60. Huo, X.S., Wasserman, P.E., Zhu, P., “A Simplified Method of Lateral Distribution of Live Load Moment,” Journal of Bridge Engineering (2002). (In press)

84. Normandin, P., and Massicotte, B., “Load Distribution in Composite Steel Box Girder Bridges,” Developments in Short and Medium Span Bridge Engineering (1994), pp. 165-176.

104. Samaan, M., Sennah, K., and Kennedy, J.B., “Distribution of Wheel Loads on Continuous Steel Spread-Box Girder Bridges,” Journal of Bridge Engineering, Vol. 7, No. 3 (May/June 2002), pp. 175-183.

110. Sennah, K.M., and Kennedy, J.B., “Literature Review in Analysis of Box-Girder Bridges,” Journal of Bridge Engineering, Vol. 7, No. 2 (March/April 2002), pp. 134-143.

111. Sennah, K.M., and Kennedy, J.B., “Load Distribution Factors for Composite Multicell Box Girder Bridges,” Journal of Bridge Engineering, Vol. 4, No. 1 (February 1999), pp. 71-78.

Cast-in-Place/Precast Concrete Tee Beam

3. Al-Mahaidi, R. Taplin, G. and Giufre, A., "Load Distribution and Shear Strength Evaluation of an Old Concrete T-Beam Bridge," Transportation Research Record No. 1696, Transportation Research Board, Washington, D.C. (2000), pp. 52-62.

16. Bakht, B., Cheung, M.S., and Aziz, T.S., "Application of a simplified method of calculating longitudinal moments to the Ontario highway bridge design code," Canadian Journal of Civil Engineering, Vol. 6, No. 1 (March 1979), pp. 36-50.

25. Burdette, E.G., and Goodpasture, D.W., "Correlation of Bridge Load Capacity Estimates with Test Data," National Cooperative Highway Research Program Report 306, Transportation Research Board, Washington, D.C. (1988).

35. Culham, G.A., and Ghali, A., "Distribution of Wheel Loads on Bridge Girders," Canadian Journal of Civil Engineering, Vol. 4, No. 1 (March 1977), pp. 57-65.

55. Hays, C., Sessions, L., and Berry, A., "Further Studies on Lateral Load Distribution Using a Finite Element Method," Transportation Research Record No. 1072, Transportation Research Board, Washington, D.C. (1986), pp. 6-14.

60. Huo, X.S., Wasserman, P.E., Zhu, P., "A Simplified Method of Lateral Distribution of Live Load Moment," Journal of Bridge Engineering (2002) (in press).

62. Imbsen, R.A., and Schamber, R.A., "Influence Surface Approach to Determine Wheel Load Distribution Factors for Rating Highway Bridges," International Conference on Short and Medium Span Bridges, Proceedings, Toronto, Canada (1982), pp. 273-287.

63. Imbsen, R.A., Liu, W.D., and Schamber, R.A., “Strength Evaluation of Existing Reinforced Concrete Bridges,” National Cooperative Highway Research Program Report 292, Transportation Research Board, Washington, D.C. (1987).

102. Reisnour, P.R., and Batla, F.A., “Finite-Element Load Distribution Factors for Multi-T-Beam Bridges,” Transportation Research Record Vol. 1, Transportation Research Board, Washington, D.C. (1984), pp. 129-135.

106. Sanders, W.W., Jr., and Elleby, H.A., “Distribution of Wheel Loads on Highway Bridges,” National Cooperative Highway Research Program Report No. 83, Transportation Research Board, Washington, D.C. (1970).

112. Shahawy, M., and Huang, D., “Analytical and Field Investigation of Lateral Load Distribution in Concrete Slab-On-Girder Bridges,” ACI Structural Journal, Vol. 98, No. 4 (July/August 2001), pp. 590-599.

Precast Solid, Voided, or Cellular Concrete Boxes

17. Bakht, B., Jaeger, L.G., and Cheung, M.S., “Transverse Shear in Multibeam Bridges,” Journal of Structural Engineering, Vol. 109, No. 4 (April 1983), pp. 936-949.

18. Bakht, B., Jaeger, L.G., Cheung, M.S., and Mufti, A.A., “The State of the Art in Analysis of Cellular and Voided Slab Bridges,” Canadian Journal of Civil Engineering, Vol. 8, No. 3 (September 1981), pp. 376-391.

44. Evans, H.R., “Simplified Methods for the Analysis and Design of Bridges of Cellular Cross-Section,” Analysis and Design of Bridges (Proceedings of the NATO Advanced Study Institute), No. 74 (1984), pp. 95-115.

Precast Concrete Channel Sections

106. Sanders, W.W., Jr., and Elleby, H.A., "Distribution of Wheel Loads on Highway Bridges," National Cooperative Highway Research Program Report No. 83, Transportation Research Board, Washington, D.C. (1970).

122. Stanton, J.F., and Mattock, A.H., "Load Distribution and Connection Design for Precast Stemmed Multibeam Bridge Superstructures," National Cooperative Highway Research Program Report 287, Transportation Research Board, Washington, D.C. (1986).

Precast Concrete Double Tee Sections

7. Arockiasamy, M., and Amer, A., "Load Distribution on Highway Bridges Based on Field Test Data," Final Report, Florida DOT HPR Study No. 0668, WPI 0510668, Job No. 99500-3512-119, Center for Infrastructure and Constructed Facilities, Florida Atlantic University, Boca Raton, Florida (1995).

23. Bishara, A.G., and Soegiarso, R., "Load Distribution in Multibeam Precast Pretopped Prestressed Bridges," Journal of Structural Engineering, Vol. 119, No. 3 (March 1993), pp. 920-937.

102. Reisnour, P.R., and Batla, F.A., "Finite-Element Load Distribution Factors for Multi-T-Beam Bridges," Transportation Research Record Vol. 1, Transportation Research Board, Washington, D.C. (1984), pp. 129-135.

112. Shahawy, M., and Huang, D., “Analytical and Field Investigation of Lateral Load Distribution in Concrete Slab-On-Girder Bridges,” ACI Structural Journal, Vol. 98, No. 4 (July/August 2001), pp. 590-599.

122. Stanton, J.F., and Mattock, A.H., “Load Distribution and Connection Design for Precast Stemmed Multibeam Bridge Superstructures,” National Cooperative Highway Research Program Report 287, Transportation Research Board, Washington, D.C. (1986).

Precast Concrete I or Bulb-Tee Sections

1. Abenroth, R.E., Klaiber, F.W., and Shafer, M.W., “Diaphragm Effectiveness in Prestressed Concrete Girder Bridges,” Journal of Structural Engineering, Vol. 121, No. 9 (September 1995), pp.1362-1369.

2. Abenroth, R.E., Klaiber, F.W., and Shafer, M.W., “Lateral Load Resistance of Diaphragms in Prestressed Concrete Girder Bridges,” Final Report, Iowa DOT Project HR-319, ISU-ERI-Ames-92076, Engineering Res. Inst., Iowa State Univ., Ames, Iowa (1991).

7. Arockiasamy, M., and Amer, A., “Load Distribution on Highway Bridges Based on Field Test Data,” Final Report, Florida DOT HPR Study No. 0668, WPI 0510668, Job No. 99500-3512-119, Center for Infrastructure and Constructed Facilities, Florida Atlantic University, Boca Raton, Florida (1995).

8. Aswad, A., and Chen, Y., “Impact of LRFD Specifications on Load Distribution of Prestressed Concrete Girders,” PCI Journal, Vol. 39, No. 5 (1994), pp. 78-89.

16. Bakht, B., Cheung, M.S., and Aziz, T.S., “Application of a simplified method of calculating longitudinal moments to the Ontario highway bridge design code,” Canadian Journal of Civil Engineering, Vol. 6, No. 1 (March 1979), pp. 36-50.

21. Barr, P.J., Eberhard, M.O., and Stanton, J.F., “Live-Load Distribution Factors in Prestressed Concrete Girder Bridges,” Journal of Bridge Engineering, Vol. 6, No. 5 (September/October 2001), pp. 298-306.

22. Bell, N.B., “Load Distribution of Continuous Bridges Using Field Data and Finite Element Analysis,” M.S. Thesis, Florida Atlantic University (1998).

25. Burdette, E.G., and Goodpasture, D.W., “Correlation of Bridge Load Capacity Estimates with Test Data,” National Cooperative Highway Research Program Report 306, Transportation Research Board, Washington, D.C. (1988).

26. Cai, C.S., Shahawy, M., and Peterman, R.J., “Effect of Diaphragms on Load Distribution of Prestressed Concrete Bridges,” Transportation Research Record, No. 1814, Transportation Research Board, Washington, D.C. (2002), pp. 47-54.

28. Chen, Y., “Distribution of Vehicular Load on Bridge Girders by the FEA using ADINA: Modeling, Simulation, and Comparison,” Computer & Structures, Vol. 72, No 1-3 (July/August 1999), pp 127-139.

30. Chen, Y., “Refined and Simplified Methods of Lateral Load Distribution for Bridges with Unequally Spaced Girders: I. Theory,” Computers and Structures, Vol. 55, No. 1 (April 1995), pp. 1-15.

32. Chen, Y., and Aswad, A., “Stretching Span Capability of Prestressed Concrete Bridges Under AASHTO LRFD,” Journal of Bridge Engineering, Vol. 1, No. 3 (August 1996), pp. 112-120.

35. Culham, G.A., and Ghali, A., “Distribution of Wheel Loads on Bridge Girders,” Canadian Journal of Civil Engineering, Vol. 4, No. 1 (March 1977), pp. 57-65.

37. Eamon, C.D., and Nowak, A.S., “Effects of Edge-Stiffening Elements and Diaphragms on Bridge Resistance and Load Distribution,” Journal of Bridge Engineering, Vol. 7, No. 5 (September/October 2002), pp. 258-266.

54. Green, T., Yazdani, N., Spainhour, L., and Cai, C.S., “Intermediate Diaphragm and Temperature Effects on Concrete Bridge Performance,” Transportation Research Record No. 1814, Transportation Research Board, Washington, D.C. (2002), pp. 83-90.

55. Hays, C., Sessions, L., and Berry, A., “Further Studies on Lateral Load Distribution Using a Finite Element Method,” Transportation Research Record No. 1072, Transportation Research Board, Washington, D.C. (1986), pp. 6-14.

58. Huo, X.S., Crouch, L.K., Ung, F., Zhu, P. and Goodwin, W.A., “Experimental Study of Optimal Erection Schedule of Prestressed Concrete Bridge Girders,” Final Report, Tennessee DOT Project No. TNSPR-RES 1188, Tennessee Technological University, Cookeville, TN (December 2002).

60. Huo, X.S., Wasserman, P.E., Zhu, P., “A Simplified Method of Lateral Distribution of Live Load Moment,” Journal of Bridge Engineering (2002) (in press).

68. Khaleel, M.A., and Itani, R.Y., “Live Load Moments for Continuous Skew Bridges,” Journal of Structural Engineering, Vol. 116, No. 9 (September 1990), pp. 2361-2373.

89. Oesterle, R.G., Glikin, J.D., and Larson, S.C., “Design of Precast Prestressed Bridge Girders Made Continuous,” National Cooperative Highway Research Program Report 322, Transportation Research Board, Washington, D.C. (1989).

106. Sanders, W.W., Jr., and Elleby, H.A., “Distribution of Wheel Loads on Highway Bridges,” National Cooperative Highway Research Program Report No. 83, Transportation Research Board, Washington, D.C. (1970).

108. Schwarz, M., and Laman, J.A., “Response of Prestressed Concrete I-Girder Bridge to Live Load,” Journal of Bridge Engineering, Vol. 6, No. 1 (January/February 2001), pp. 1-8.

109. Sengupta, S., and Breen, J.E., “The Effect of Diaphragms in Prestressed Concrete Girder and Slab Bridges,” Res. Report 158-1F, Project 3-5-71-158, Center for Highway Res., Univ. of Texas at Austin, TX (1973).

112. Shahawy, M., and Huang, D., “Analytical and Field Investigation of Lateral Load Distribution in Concrete Slab-On-Girder Bridges,” ACI Structural Journal, Vol. 98, No. 4 (July/August 2001), pp. 590-599.

118. Smith, K.N., and Mikelsteins, I., “Load Distribution in Edge Stiffened Slab and Slab-on- Girder Bridge Decks,” Canadian Journal of Civil Engineering, Vol. 15, No. 6 (December 1988), pp. 977-983.

122. Stanton, J.F., and Mattock, A.H., “Load Distribution and Connection Design for Precast Stemmed Multibeam Bridge Superstructures,” National Cooperative Highway Research Program Report 287, Transportation Research Board, Washington, D.C. (1986).

132. Tobias, D.H., Anderson, R.E., Khayyat, S.K., Uzman, Z.B., and Riechers, K.L., “Simplified AASHTO LRFD Girder Live Load Distribution in Illinois,” Journal of Bridge Engineering (In press).

Wood Beam

16. Bakht, B., Cheung, M.S., and Aziz, T.S., “Application of a simplified method of calculating longitudinal moments to the Ontario highway bridge design code,” Canadian Journal of Civil Engineering, Vol. 6, No. 1 (March 1979), pp. 36-50.

50. GangaRao, H., “Response of Stressed Timber T- and Box-Beam Bridges,” Proceedings of the Structures Congress, Atlanta, GA (April 1994), pp. 701-706.

135. Wipf, T.J., Klaiber, F.W., and Sanders, W.W. Jr., “Load Distribution Criteria for Glued-Laminated Longitudinal Timber Deck Highway Bridges,” Transportation Research Record No. 1053, Transportation Research Board, Washington, D.C. (1986), pp. 31-40.

Solid/Voided Slab

4. Amer, A., Arockiasamy, M., and Shahawy, M., “Load Distribution of Existing Solid Slab Bridges Based on Field Tests,” Journal of Bridge Engineering, Vol. 4, No. 3 (August 1999), pp. 189-193.

7. Arockiasamy, M., and Amer, A., “Load Distribution on Highway Bridges Based on Field Test Data,” Final Report, Florida DOT HPR Study No. 0668, WPI 0510668, Job No. 99500-3512-119, Center for Infrastructure and Constructed Facilities, Florida Atlantic University, Boca Raton, Florida (1995).

16. Bakht, B., Cheung, M.S., and Aziz, T.S., “Application of a simplified method of calculating longitudinal moments to the Ontario highway bridge design code,” Canadian Journal of Civil Engineering, Vol. 6, No. 1 (March 1979), pp. 36-50.

18. Bakht, B., Jaeger, L.G., Cheung, M.S., and Mufti, A.A., “The State of the Art in Analysis of Cellular and Voided Slab Bridges,” Canadian Journal of Civil Engineering, Vol. 8, No. 3 (September 1981), pp. 376-391.

25. Burdette, E.G., and Goodpasture, D.W., “Correlation of Bridge Load Capacity Estimates with Test Data,” National Cooperative Highway Research Program Report 306, Transportation Research Board, Washington, D.C. (1988).

41. El-Behairy, S.A., Soliman, M.I., and Fouad, N.A., “Nonlinear Behavior of Reinforced Concrete Voided Slab Bridges,” Developments in Short and Medium Span Bridge Engineering, Vol. 1 (1990), pp. 215-227.

46. Frederick, G.R., and Tarhini, K.M., “Wheel Load Distribution in Concrete Slab Bridges,” Proceedings of the Eighth International Conference on: Computing in Civil and Building Engineering, Vol. 2 (2000), pp. 1236-1239.

55. Hays, C., Sessions, L., and Berry, A., “Further Studies on Lateral Load Distribution Using a Finite Element Method,” Transportation Research Record No. 1072, Transportation Research Board, Washington, D.C. (1986), pp. 6-14.

63. Imbsen, R.A., Liu, W.D., and Schamber, R.A., "Strength Evaluation of Existing Reinforced Concrete Bridges," National Cooperative Highway Research Program Report 292, Transportation Research Board, Washington, D.C. (1987).

106. Sanders, W.W., Jr., and Elleby, H.A., "Distribution of Wheel Loads on Highway Bridges," National Cooperative Highway Research Program Report No. 83, Transportation Research Board, Washington, D.C. (1970).

118. Smith, K.N., and Mikelsteins, I., "Load Distribution in Edge Stiffened Slab and Slab-on-Girder Bridge Decks," Canadian Journal of Civil Engineering, Vol. 15, No. 6 (December 1988), pp. 977-983.

Miscellaneous

11. Bakht, B., "Load Distribution in Laminated Timber Decks," Journal of Structural Engineering, Vol. 114, No. 7 (July 1988), pp. 1551-1570.

12. Bakht, B. and Jaeger, L.G., *Bridge Analysis Simplified*, McGraw-Hill Book Company, New York (1985).

20. Barker, R.M., and Puckett, J.A., "Design of Highway Bridges – Based on AASHTO LRFD Bridge Design Specifications," John Wiley & Sons, Inc., New York (1997).

53. Goodrich, B.L., and Puckett, J.A., "Comparison of LFR and LRFR Bridges," National Concrete Bridge Conference, National Concrete Bridge Association, Nashville, TN (October 2002).

64. Jaeger, L.G., and Bakht, B., *Bridge Analysis by Microcomputer*, McGraw-Hill Book Company, New York (1989).

72. Lichtenstein, A.G., "Manual for Bridge Rating Through Load Testing," National Cooperative Highway Research Program Research Results Digest No. 234 (November 1998).

79. Mlynarski, M., and Puckett, J.A., Bridge Software Validation Guidelines, Final Report, NCHRP 12-50, Washington, D.C. (final submitted, not yet published).

81. Moses, F., "Calibration of Load Factors for LRFD Bridge Evaluation," National Cooperative Highway Research Program Report 454, Transportation Research Board, Washington, D.C. (2001).

83. Mourad, S., and Tabsh, S.W., "Deck Slab Stresses in Integral Abutment Bridges," Journal of Bridge Engineering, Vol. 4, No. 2 (May 1999), pp. 125-130.

85. Nowak, A.S., "Bridge Load Models," Bridges: Part of the Transport System. Proceedings of the AUSTROADS Bridges Conference (November 1991), pp. 503-523.

86. Nowak, A.S., "Calibration of LRFD Bridge Design Code," National Cooperative Highway Research Program Report 368, Transportation Research Board, Washington, D.C. (1999).

87. Nowak, A.S., and Hong, Y-K., "Bridge Live-Load Models," Journal of Structural Engineering, Vol. 117, No. 9 (September 1991), pp. 2757-2767.

90. Puckett, J.A., "Compound Strip Analysis of Continuous Elastic Plates," In partial fulfillment for the Ph.D. degree, Colorado State University, Ft. Collins, CO. 1983.

91. Puckett, J.A., “Application of the Compound Strip Method for the Analysis of Slab-Girder Bridges,” Journal of Structural Engineering, Vol. 112, No. 1 (March 1986).

94. Puckett, J.A., and Gutkowski, R.M., “Compound Strip Analysis of Continuous Elastic Plates,” Journal of Structural Engineering, Vol. 112, No. 1 (January 1986).

95. Puckett, J.A., and Lang, G.J., “Compound Strip Methods for the Free Vibration Analysis of Continuous Rectangular Plates,” Journal of the Mechanics Division, Vol. 112, No. 12 (December 1986).

96. Puckett, J.A., and Lang, G.J., “Compound Strip Method for the Frequency Analysis of Continuous Plates,” Thin-Walled Structures – An International Journal, Vol. 7, No. 8 (1989), pp. 165-182.

97. Puckett, J.A., and Mlynarski, M., “Bridge Software Validation Guidelines,” Transportation Research Record No. 1696, Vol. 2, Transportation Research Board, Washington, D.C. (2001).

98. Puckett, J.A., and Wiseman, D.L., “The Compound Strip Method for Folded Plates with Connecting Elements,” Journal of Structural Engineering, Vol. 117, No. 1 (January 1991).

99. Puckett, J.A., Wiseman, D.L., and Chong, K.P., “Compound Strip Method for the Buckling Analysis of Continuous Plates,” Thin-Walled Structures – An International Journal, Vol. 5, No. 5 (1987), pp. 385-402.

100. Puckett, J.A., Mlynarski, M., Jablin, M., and Clancy, C., “Bridge Software Validation Guidelines,” Fifth International Bridge Engineering Conference, Tampa, FL (April 2000). (TRB Review)

105. Sanders, W.W., Jr., “Distribution of Wheel Loads on Highway Bridges,” National Cooperative Highway Research Program, Synthesis of Highway Practice, Report No. 111, Transportation Research Board, Washington, D.C. (November 1984).

129. Thompson, P.D., Duray, J.A., Puckett, J.A., and Campbell, J.J., “The Application of Object Technology in AASHTO’s New Bridge Load Rating and Design Systems,” The First International Conference on New Information Technologies for Decision Making in Civil Engineering, Montreal (1998). (TRB review)

130. Thompson, P.D., Duray, J.A., Campbell, J.J., Puckett, J.A., Wright, B., “VIRTIS: AASHTO’s New Bridge Load Rating System,” Transportation Research Circular 448, Eighth International Bridge Management Conference, Denver, Colorado (June 2000).

136. Wiseman, D.L., and Puckett, J.A., “Applications of the Compound Strip Method for Folded Plates with Connecting Elements,” Journal of Structural Engineering, Vol. 117, No. 1 (January 1991).

139. Zokaie, T., and Imbsen, R.A., “Distribution of Wheel Loads on Highway Bridges,” NCHRP 12-26 Project Report, Transportation Research Board, National Research Council, Washington, D.C. (1993).

140. Zokaie, T., Imbsen, R.A., and Osterkamp, T.A., “Distribution of Wheel Loads on Highway Bridges,” Transportation Research Record No. 1290, Transportation Research Board, Washington, D.C. (1991), pp. 119-126.

142. Zokaie, T., Mish, K.D., and Imbsen, R.A., “Distribution of Wheel Loads on Highway Bridges,” NCHRP 12-26 Project Final Report, Volume 2, Transportation Research Board, National Research Council, Washington, D.C. (1991).

143. Zokaie, T., Mish, K.D., and Imbsen, R.A., “Distribution of Wheel Loads on Highway Bridges,” NCHRP 12-26 Project Final Report, Volume 3, Transportation Research Board, National Research Council, Washington, D.C. (1993).

144. Zuraski, P., “Continuous-Beam Analysis for Highway Bridges,” Journal of Structural Engineering, Vol. 117, No. 1 (January 1991).

Lacking Information

We have a very limited amount of information in the following areas:

- post-tensioned bridges
- wood beam bridges
- precast channel sections