Report on Flexural Live Load Distribution Methods for Evaluating Exisiting Bridges

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This report provides a synthesis of the topic of flexural live load distribution and its applicability to concrete bridges. Flexural live load distribution is critical to describing how loads are transmitted through a bridge system. This report is intended to provide engineers, including load rating engineers, with basic guidance on the methods and tools available for determining live load distribution behavior of in-service bridges. Included in the report are descriptions, a brief history, and background of the flexural load distribution phenomena and a summary of design and analysis methods used to describe the phenomena in practice. A series of case studies are presented in the latter part of the report to serve as a comparison summary of commonly used live load distribution methods and their performance in describing the behavior of in-service structures. The report also provides performing bridge load ratings with a practical synopsis of the various methods available for determining the live load distribution factor. While this report is limited to flexural live load distribution, it provides the foundation for a future committee guide on the in-service evaluation of concrete bridges.

Keywords: bridge analysis; bridge load rating; distribution factor; equivalent beam analysis; finite element; grillage analysis; live load testing; load resistance; transverse flexural load distribution.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Maintenance of an aging transportation infrastructure, including concrete bridges, is essential to the sustainability of resources and economic prosperity. With a national inventory of more than 600,000 bridges in the United States, 66 percent of which are concrete, maintenance and preservation represent a challenge for transportation agencies (Federal Highway Administration 2014). For these agencies, the challenge is to avoid or minimize bridge replacement and rehabilitation in the face of increased traffic volume and truck loads, along with dwindling financial resources.

Transportation agencies are responsible for ensuring both the safety and functionality of these bridges, and meeting this challenge requires a realistic measure of the actual behavior and in-service performance. This characterization of behavior is essential to determine the actual load-carrying capacity or remaining capacity of a bridge, which is typically determined through a processed called load rating. Load rating of a bridge defines the expected resistance or capacity based on its existing condition state and operating environment. As with bridge design, a challenge that exists for describing a bridge's capacity is the complex system interaction that exists amongst the superstructure components. For example, in a beam-slab bridge, the complexity is derived from the coupled interaction of two-way plate behavior within the bridge deck and the one-way beam behavior inherent to the girders. For both design and evaluation, a methodology for transverse distribution of loads, or live load distribution, is typically used to represent this phenomenon and provide a method to quantify relative load sharing behavior within the system.

In practice, this phenomenon is typically defined using prescriptive formulas that simplify the complex behavior into simple factors, but in recent decades, several refined methods for determining live load distribution have evolved. These methods provide alternative mechanisms to describe live load distribution behavior, which can often be more representative than the empirical methods included in most bridge design codes and specifications. The advantage of considering these methods is that they have the potential to describe the physical phenomenon and actual load distribution behavior, which in turn provides the bridge engineer with a mechanisms to make more informed decisions regarding load restrictions, maintenance, and replacement of existing bridges.

1.2—Scope

This report is intended for the bridge engineering community, particularly engineers responsible for bridge load rating, to provide basic guidance on the methods and tools available for determining live load distribution behavior of in-service bridges. The objective is to present guidance on available methods for determining live load distribution, including approximate formulas, structural analysis, or load testing. The selection of a particular method of analysis is presented within the context of the intended level of refinement and bridge type, such as slab, beam-slab, and box girder. Included in this report are descriptions, a brief history, and background of the flexural load distribution phenomena and a summary of design and analysis methods used to describe the phenomena in practice. This report provides an overview of criteria for transverse load distribution, including their limitations and acceptability; a summary and description of the use of refined methods of analyses for transverse load distribution; and load test methods. A series of case studies are presented in the latter part of the report to serve as a comparative analysis of commonly used live load distribution methods and their performance in describing the behavior of in-service structures.

While this distribution phenomenon is relevant to a variety of force effects, this report focuses exclusively on flexure. The treatment of shear is a topic of future work by the committee and will be part of a guide on the in-service evaluation of concrete bridges, but is beyond the scope of this report. For a treatment of shear load distribution, the reader is encouraged to review existing literature on the topic (Bakht et al. 1983; Ebeido and Kennedy 1995, 1996; Modjeski and Masters Inc. 2002; Barr and Amin 2006; Suksawang et al. 2013).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

B = width of bridge, ft (m)
C = capacity
DC = dead load effect due to structural components and attachments
DF = lateral load distribution factor (also designated as g)
DW = dead load effect due to wearing surfaces and utilities
d_e = roadway part of overhang
F = amplification factor
IM = dynamic load allowance
k = number of girders
L = span of the bridge, ft (m)
LL = live load effect
$M_{g,ave}$ = average moment per girder
m = multiple presence factor
n = number of wheel lines of applied loading
P = permanent loads other than dead loads
S = center-to-center spacing of longitudinal web lines or girders, ft (m); also spacing of floor beams, ft (m)
w_j = ratio section modulus of the i-th girder to section modulus of typical interior girder
ε_j = bottom flange strain at the i-th girder
γ_{DC} = LRFD load factor for structural components and attachments
γ_{DW} = LRFD load factor for wearing surfaces and utilities
γ_{LL} = evaluation live load factor
γ_P = LRFD load factor for permanent loads other than dead loads

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” https://www.concrete.org/store/productdetail.aspx?ItemID=CT13. Definitions provided herein complement that resource.

beam slab—bridge system where the concrete slab or bridge deck is not supported by beams or girders and serves as the primary superstructure element or load-resisting component of the bridge.

composite beam-slab—member produced by interconnecting separate beam and slab; the connections have sufficient stiffness to ensure strain compatibility between components under service and sufficient strength to ensure the member strength is limited by material capacities in the individual components.

diaphragm—transverse member placed between the primary load-carrying elements of a superstructure system to distribute stresses and improve strength and rigidity.

dynamic load allowance (impact factor)—increase in the applied static live load force effects that account for the dynamic interaction between the bridge and moving vehicles.

effective width—reduced width of a concrete slab with an assumed uniform stress distribution, which produces the same effect on the behavior of a structural member as the actual slab with its non-uniform stress distribution.

finite difference method (differences)—method of analysis in which the governing differential equation is satisfied at discrete points on the structure.

finite element method (element)—method of analysis in which a structure is discretized into elements at nodes, the shape of the element as well as the displacement and/or stress fields are assumed, partial or complete compatibility is maintained among the element interfaces, and nodal displacements are determined by using energy variational principles or equilibrium methods.

floor beam—primary horizontal member spanning in the transverse direction relative to the general bridge alignment.

grillage analogy method—flexibility or stiffness method of analysis in which all or part of a superstructure is discretized into orthotropic planar grid components that represent the characteristics of the structure.

harmonic method—method of analysis in which the load model is subdivided into suitable parts, allowing each part to correspond to one term of a convergent infinite series by which structural deformations are described. See also **series method**.

lever rule—upper bound solution on the distribution of forces in a slab-on-girder bridge in which interior girders are assumed be hinged at the deck/girder intersection and a statical summation of moments about one point is used to calculate the reaction at a second point

live load distribution factor—fraction used to describe the portion of the total live load on the elements of a superstructure system, which represents a simplification of the complex bridge system behavior for design and analysis.

overhang—outward projection of a bridge slab that extends over the exterior beam.

refined method—method that considers the entire superstructure as one integral unit or system; for example, equivalent beam analysis, classical plate, grillage analogy analysis, three-dimensional frame analysis, and finite element analysis.

secondary member—member that does not carry calculated live loads or a member in which stress is not normally evaluated in the analyses; for example, bracing members and parapets.

series method—method of analysis in which the load model is subdivided into suitable parts, allowing each part to correspond to one term of a convergent infinite series by which structural deformations are described. See also **harmonic method**.

skew angle—angle measured between the axis of the substructure and a line perpendicular to the longitudinal axis of the superstructure.

slab-on-girder—bridge system in which a slab is placed on top of the girders, either composite or noncomposite with the girder.

spine—separate box on a multibox bridge.

transverse live load distribution—describes the load transfer mechanism from the vehicular live loads through the bridge system into the primary load-carrying superstructure members or the load fraction that is resisted by an individual superstructure primary member.

CHAPTER 3—BASIS OF CODE CRITERIA FOR TRANSVERSE LIVE LOAD DISTRIBUTION

3.1—Introduction

This chapter discusses the limitations and applicability of the various bridge design codes and specifications described in the previous chapter, specifically the standard transverse live load distribution methods predominantly used in North America. To use the design codes and specifications, bridges must meet certain criteria. This includes limits on parameters such as span length, slab thickness, girder spacing, and longitudinal stiffness. The limits include both minimum and maximum values. The distribution of vehicular live load on bridges is a major factor in determining bridge capacity and serviceability, which are crucial parameters in determining safety and economy.

Where reference is made to the various design specifications, this document only highlights specific aspects of the specifications and the reader is encouraged to reference the specification directly. There has been a great deal of research on the accuracy of standard live load distribution methods used in bridge design codes and specifications (Khaleel and Itani 1990; Zokaie et al. 1991; Arockiasamy et al. 1997; Kim and Nowak 1997; Amer et al. 1999; Bridge Diagnostics Inc. 1999; Barney et al. 2000; Zokaie 2000; Barr et al. 2001; Conner and Santosuosso 2002; Wang and Puckett 2002; Song et al. 2003; Sotelino et al. 2004; Cai 2005; Puckett 2005; Harris 2010). These references provide additional technical guidance to the reader and can be used as a technical supplement to the summaries of the bridge design codes and specifications that are presented in this section. This chapter focuses primarily on the standard transverse live load distribution methods that are predominantly used in North America.

3.2—Transverse load distribution

Transverse live load distribution describes the load transfer mechanism from the vehicular live loads through the bridge system into the primary load-carrying superstructure members. Terms related and often interchanged with “transverse live load distribution” include “load distribution” and “distribution factors”. Transverse live load distribution is a function of bridge geometry, the connections between the various bridge elements, and the relative stiffness of components in both the transverse and longitudinal load directions.

Several methods exist for the determination of transverse live load distribution in bridges. The most commonly used methods are empirical formulas included in various bridge design codes and specifications (AASHTO 2002, 2011, 2014; CAN/CSA-S6; AREMA 2009). Numerical techniques that vary in sophistication are also used: beam analogy techniques, classical plate model, grillage analyses, and finite element analyses. In addition, load testing can be performed to directly measure load sharing behavior. The results from load testing are recognized as the most accurate method for determining transverse live load distribution behavior, but these tests can be costly, challenging to execute, and are not applicable during the design phase. Similarly, refined methods of analysis have become well accepted within the bridge community and are proven to yield reliable results, but when compared to the use of empirical formulas, their implementation is typically more complex. Various forms of empirical formulas for describing live load distribution have been successfully used in design practice since the 1930s; these formulas are typically simple to implement and generally provide conservative and suitable estimates of the system behavior.

3.3—Empirical formulas for transverse live load distribution

Empirical equations are based predominantly on geometric factors such as girder spacing, span length, and deck thickness, and provide sufficient accuracy for most common bridge structures. The equations available within the North American codes can be classified as approximate methods and use an approach that simplified the complex system phenomena or live load distribution response into a distribution factor, which defines the relative force effect that must be designed for. These formulas for distribution factors are typically specific to a specific force effect (for example, moment or shear) and are often further categorized based on member location (that is, interior or exterior) and loading scenario (that is single or multiple truck loading). The following sections provide basic background information on the various bridge design codes used for concrete bridges in North America. This background information includes a summary of the general parameters used in the formulation, a limited history on their development, and a discussion on the limitations.

In general, bridges that have insufficient load capacity for legal truck loads based on approximate methods of analyses should be reanalyzed using more refined analytical tools to establish an acceptable capacity. In the case of skewed or irregularly shaped structures, actual distribution of live loads varies substantially from the distribution values determined using empirical equations and requires further modification to the basic form of the equations.

Identification of the most appropriate refined method of analysis for use depends on bridge configuration as well as bridge type. This is discussed in detail in subsequent chapters. If refined methods of analyses reveal that bridges have insufficient load capacity, then load testing may provide a more accurate determination of bridge stiffness, structural behavior, and live load sharing behavior.

3.4—AASHTO Standard Specification for Highway Bridges

Before the introduction of the AASHTO LRFD (1994), distribution factors used for design and evaluation were determined using the provisions of AASHTO Standard Specification for Highway Bridges (AASHTO 2002), which uses a simple ratio of girder spacing to a constant, often