Engineering Structures 153 (2017) 1–16

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Time-variant reliability analysis of widened deteriorating prestressed concrete bridges considering shrinkage and creep

Bing Tu [a], Zhi Fang [a,*], You Dong [b], Dan M. Frangopol [c]

[a] College of Civil Engineering, Hunan University, Changsha, Hunan 410082, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[c] Department of Civil and Environmental Engineering, Engineering Research Center for Advanced Technology for Large Structural Systems (ATLSS Center), Lehigh University, Bethlehem, PA 18015-4729, USA

ARTICLE INFO

Article history:
Received 4 July 2017
Revised 27 September 2017
Accepted 28 September 2017
Available online 14 October 2017

Keywords:
Widened concrete bridge
Live-load distribution factor
Shrinkage and creep
Corrosion
System reliability

ABSTRACT

Nowadays, bridge widening has become an economic option to tackle the increasing demand of the traffic volume and to enhance the capacity of existing highway bridges. Thus, relevant studies on the performance assessment of widened bridges are needed. This paper presents a computational probabilistic framework for time-variant reliability analysis of widened concrete highway bridges in a systematic manner considering the effects of live-load redistribution, structural deterioration, and concrete shrinkage and creep. Specifically, differences and inconsistences between the new and existing structures regarding live-load distribution, reinforcement corrosion, and concrete shrinkage and creep are considered. A finite element grillage model is constructed to investigate live-load distribution factors and internal axial forces caused by concrete shrinkage and creep. The uncertainties associated with shrinkage and creep effects are accounted for within the probabilistic framework. The flexural moment resistance of the bridge girder is computed considering the combined effects of the shrinkage-and-creep-induced axial force and structural deterioration. Ultimately, the system reliability of the widened bridge is calculated. The proposed probabilistic framework is applied to a widened prestressed concrete T-girder bridge.

1. Introduction

Due to limited budget and conservative prediction of increase of traffic volume, a considerable number of narrow bridges were built previously all over the world. With the rapid growth of traffic volume, many of these existing bridges became functionally obsolete due to insufficient width. Compared with complete replacement or building a new bridge, widening these bridges is generally more economical and effective [1]. For most widened concrete bridges, in order to improve structural integrity, the superstructures of the new and existing bridges are connected by longitudinal splice joints [2]. The static and long-term behavior of the widened bridge, considering the interaction between new and existing bridges, are much more complex than those in the case of treating these bridges separately [3,4]. However, nearly all bridge widening guidelines suggest that standards and guides used for new bridges can also be applied for the widened bridges without considering the interaction between the new and existing bridges [1,5–8]. Thus, it can be concluded that the specified design and assessment methodology for widened bridges have not been well established and, therefore, relevant studies are needed.

Nowadays, the reliability-based load and resistance factor design (LRFD) method dominates the design philosophy for most current design codes including the Chinese code for design of highway reinforced concrete and prestressed concrete bridge and culverts (JTG D62-2004) [9], the model code 2010 [10], and the AASHTO LRFD Bridge Design Specifications [11], among others. The structural reliability index is also recognized as the fundamental performance indicator for structural safety and performance assessment of existing structures [12–17]. Thus, relevant reliability studies of widened bridges are necessary.

Within the performance assessment of widened bridges, the live-load redistribution should be computed firstly. Nie et al. [18] modified the conventional rigid-jointed girder method (RJGM) to compute the transverse distribution coefficient of concrete girders that are widened with steel-concrete composite beams. Chen et al. [19] proposed a general hinge-jointed slab method (HJSM) for the computation of the lateral distribution factor of widened prestressed concrete hollow slab bridge. Chang et al. [20] investigated the live-load redistribution behavior of widened T-girder and hollow slab bridge using finite element (FE) grillage model. Based on

* Corresponding author.
E-mail address: fangzhi@hnu.edu.cn (Z. Fang).

https://doi.org/10.1016/j.engstruct.2017.09.060
0141-0296/

these studies, it can be concluded that the analytical methods (e.g., RJGM, HJSM) are only suitable for certain types of widened bridges, while the FE-model-based method can serve as a general approach for live-load redistribution analysis of widened bridges.

Another well-recognized mechanical characteristic of widened concrete bridges is the shrinkage and creep difference between new and existing girders. This difference could result in significant time-dependent internal stresses [4,21–23]. Fang et al. [24] investigated the internal forces induced by shrinkage and creep in widened box-girder bridge using FE, and compared the bending moment capacity of the box-girder before and after widening by sectional nonlinear analysis. The results indicated that as the axial compressive force induced by shrinkage and creep changes the failure mode of the existing box-girder (i.e., from flexural failure to compressive-flexural failure), the bending moment capacity of the existing box-girder increases. Thus, it is of vital importance to integrate these effects associated with concrete shrinkage and creep into the structural reliability analysis process. In addition, it should be noted that most studies on shrinkage and creep effects in widened bridges are deterministic. Uncertainties associated with concrete shrinkage and creep will be addressed in this paper.

As bridges are usually directly exposed to environmental attack, their capacities will decrease over time. For reinforced concrete and prestressed concrete bridges, corrosion of reinforcement steel is the primary source of structural deterioration [25–27]. During the past decades, the effects of reinforcement corrosion on the reliability of existing concrete structures have been investigated [28–34]. Two main conclusions can be drawn from these studies. Firstly, reinforcement corrosion plays an important role in time-variant reliability analysis of existing concrete bridges, especially for those exposed to chloride-prone environments [35–37]. Secondly, the deterioration process mainly depends on corrosion initiation time and corrosion rate. As there exist differences in the construction time (or service time) and design profiles (e.g., concrete material properties, thickness of concrete cover) between new and existing girders, the extent of reinforcement corrosion can vary between them. Therefore, it is necessary to consider, for widened concrete bridges, the corrosion progress (i.e., corrosion initiation time and corrosion rate) using time-variant reliability analysis.

Overall, bridge widening has become an economic option to enhance the capacity of existing bridges. However, the reliability analysis of widened bridges is still in its infancy. The interactions between new and existing girders, including live-load redistribution, concrete shrinkage and creep effects, and different reinforcement corrosion, deem to have significant effects on performance of the widened concrete bridges. All these effects should be carefully considered within the reliability assessment process in a systematic and probabilistic manner. Furthermore, the reliability analysis should be conducted at a system level to account for the correlations among different girders and the redundancy of the bridge system. This paper aims to propose a probabilistic approach to compute the time-variant reliability of widened concrete bridges considering live-load redistribution, concrete shrinkage and creep as well as the difference in reinforcement corrosion between new and existing girders. To conduct this study, firstly, live-load distribution factors and internal axial forces caused by concrete shrinkage and creep are computed using a FE grillage model, and an age-adjusted effective modulus (AAEM)-based algorithm is proposed within the FE analysis to assess the shrinkage and creep effects. The uncertainties associated with the shrinkage and creep effects are accounted for within the computation process. Subsequently, considering the combined effects of reinforcement corrosion and the shrinkage-and-creep-induced forces, the probabilistic flexural moment resistance of girder components is assessed using Monte Carlo Simulation (MCS). Then, the superstructure of widened concrete bridge is modeled as a series-parallel system, in which the correlation of resistances between different girder components is considered. Finally, the reliability index of girder components and the bridge system are computed. In order to demonstrate the application of the proposed approach, a widened prestressed concrete T-girder bridge is considered.

2. Flowchart of reliability assessment of widened concrete bridge

The proposed methodology is integrated using three modules: structural analysis of capacity and demand, probabilistic analysis, and system reliability analysis modules, as shown in Fig. 1. Firstly, structural analysis of widened concrete bridge is conducted considering the interactions between new and existing girders. The output of this module is the demand (i.e., live-load effect) and resistance of each girder component. Then, the probabilistic analysis module is developed to consider the uncertainties associated with the variables involved in the first module. The simulation methods (e.g., MCS and Latin Hypercube Sampling (LHS) [38]) can be used to generate these random variables. Finally, a system reliability model that describes the behavior of the widened bridge system and the relationship of individual girder components to the overall system is introduced. The reliability of the investigated widened bridge system can be calculated using First order reliability method (FORM)/Second order reliability method (SORM). In order to account for time-dependent effects (i.e., structural deterioration, concrete shrinkage and creep), the proposed methodology is repeated for each time step during the investigated time interval.

3. Live-load redistribution of widened bridge

3.1. Lateral live-load distribution

For a bridge superstructure with multi-girders, the live-load effect on an individual girder is generally computed as [39]

$$F_{refined,i} = F_{beamline} \times g_{F,i} \tag{1}$$

where $F_{refined,i}$ = the maximum live-load flexural moment or shear force in a certain girder for all possible load combinations; $F_{beamline}$ = the maximum flexural moment or shear force determined from a simple beam-line analysis under one lane of traffic; and $g_{F,i}$ = live-load distribution factor (LLDF), which reflects the distribution characteristic of live load in lateral direction.

LLDF is related with many geometric and material parameters, such as girder type, girder spacing, span length, traffic lane arrangement, transverse connection stiffness and sectional longitudinal stiffness, among others [40–42]. As these parameters may change during the bridge widening process, LLDF as well as live-load effect of an individual girder associated with new and existing bridges should be updated accordingly.

Though explicit formulas of LLDF are available in various bridge design codes, such as AASHTO LRFD Specifications [11], these simplified formulas are generally conservative, and are only applicable to certain types of bridges, such as slab-girder superstructures with uniform girder spacing and longitudinal stiffness [43]. For widened bridges, the type of superstructure may vary, and the spacing as well as longitudinal stiffness of girder component of new and existing bridges are usually different. Therefore, a more accurate and systematic method for computation of LLDF of widened structures should be established. Herein, the grillage model is used to compute the LLDF. This method will be described in the following section.

3.2. Grillage model for live-load effect analysis

The grillage-model-based method is adopted herein to compute the live-load effects on bridges before and after widening. Grillage