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Analysis of Shear Live Load Girder Distribution Factors in Integral bridges using the Finite Element Method

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***Abstract*— *This paper studies the accuracy of AASHTO Standard Specifications and AASHTO LRFD design specifications girder distribution factors (GDFs) equations and their applicability to integral abutment bridges (IABs). A three-dimensional (3D) finite element (FE) model of the Scotch Road integral abutment bridge was developed using the finite element software ABAQUS/Cae. The bridge was subjected to vehicular live loading in single and multiple lanes in the FE model(s). The FE model was calibrated using load-displacement data obtained from field testing due to static truck loading. A comparison between the GDFs obtained from the FE models to those computed using both design codes was performed to evaluate their accuracy. A limited parametric study was conducted to evaluate crucial design parameters such as bridge deck thickness, span length, and piles lengths. The results showed that AASHTO LRFD GDFs equations are more conservative compared to those of AASHTO LFD equations in all cases. However, GDFs from the FE models compared more favorably to those calculated based on both design codes for the case single lane loading.*

Keywords*— *Girders Shear Distribution Factor Equations; AASHOT LRFD Girder Shear Distribution Equations; AASHTO LFD Girder Shear Distribution Equations; Finite Element Model; Integral Abutment Bridges.

I. INTRODUCTION

Wheel load distribution is of significant importance in the design of highway bridges. It is used in the preliminary sizing of bridge members as well as calculating their strength and serviceability (NCHRP 12-26/1). Therefore, the relevance and importance of wheel load disruption factors can be deduced.The AASHTO standard equations that were originally developed in the early 1930s are among the most established equations used to calculate the live load distribution factors (LDF) (NCHRP 12-26/1; and Suksawang*et al* , 2007). The AASHTO standard equations form is very simple,the equations compute the girder distribution factor (GDF) by dividing the girdersspacing (S) by a constant (D) that depends on the bridge type; this leads them to also be known as the S over D equations (Sotelino*et al*, 2004; and Suksawang*et al*, 2007). The simplicity of the AASHTO standard equations gives them an advantage as they are easy to use and it was found that they do generate valid results for bridges of typical geometry (Zokaie, 2004). However, it was noted that their accuracy decrease when used on bridges with unusual geometries and dimensions. Examples of such variations include longer or shorter than normal bridge spans, additionally they did not consider a wide range of bridges types or account for bridges' skew which is common for Highway Bridge geometry (Zokaie, 2004). The shortcomings of the AASHTO standard equations led to the development of the AASHTO LRFD specifications which introduced new equations for the computation of GDFs. The AASHTO LRFD equations were the result of the work done in the NCHRP 12-26. They were developed based on elastic finite element analysis (Sotelino*et al*, 2004). Unlike the AASHTO standard equations they consider a wider range of bridge types, and parameters. A notable advantage of the AASHTO LRFD equations is that they account for skew if the skew angle is more than 30°. This is very advantageous since a lot of the modern highway bridges are skewed (Brendler, 2015).However, accounting for more parameters and a widerrange of bridges means the equations are relatively more complex and computationally demanding especially when compared to AASHTO Standard Specifications equations.

The objective of this work is to evaluate the accuracy of AASHTOStandard equations for shear GDFs versus those adopted by AASHTO LRFD design specifications. The ASSHTO standard equations and the AASHTO LRFD equations used to calculate the girders moment distributing factors have been extensively studied (Brendler*et al*, 2016; Eom, *et al* 2001; Zokaie, 2004; Zokaie, 2005; Kim *et al*, 1997; Nowak, 1995; and Suksawang *et al*, 2007).Therefore, this work will focus on the evaluation of theAASHTO Standard Specifications and the AASHTO LRFD shear GDFs equations. To achieve this objective a parametric study was conducted on the Scotch Road Bridge Located in Trenton, N.J. The Scotch Road Bridge is an integral abutment bridge (IAB), where the superstructure and the substructure move in unison when subjected to thermal loads. This is achieved by directly connecting the deck andgirders to the abutment (White, 2007; and Arsoy*et al*,1999). IABs can be classified into two categories (i) fully integral Abutment bridges (FIABs), and (ii) Semi-Integral Abutment bridge (SIABs) in which the girders rest on bearings. In the early 1960s IABs started to gain traction and popularity among designers (White, 2007). The University of Illinois at Champaign-Urbana survey found that there are approximately 9000 FIABs and 4000 SIABs in the United States (White, 2007). The approach of designing a bridge without thermal expansion joints was developed due the assortment of problems that arose at bridges withthermal expansion joints. The major issue with thermal expansion joints is leakage in the expansion joints and seals allowing runoff water in, which in turn leads to the corrosion of the expansion joints bearings (Brendler*et al*, 2017). As it currently stands there are no unified design criteria for IABs in the United States or Europe but, a report by the New York State Department of Transportation concluded that the design standards are similar (White, 2007)). IABs doesn't only face the problems resulting from thermal expansion joints but the cyclic loading resulting from the bridge movement causes backfill settlement, and cracks in the approach slabs(Brendler*et al*, 2017).

II. RESEARCH OBJECTIVES

The goal of this research is to evaluate the accuracy of the AASHTO LRFD and AASHTO Standard Specifications shear GDFs equations in predicting live load distribution in integral bridges. To that end, the finite element software ABAQUS/Cae was used to develop 3D models of the Scotch Road Bridge. The models were analyzed under different loading conditions using a standard AASHTO HS20-44 design truck. Three loading cases were considered (i) one lane loaded, (ii) two lanes loaded, and (iii) three lanes loaded (including the auxiliary lane). A parametric study was conducted to study the impact of influential parameters on the shear GDFs, and hence, the live load distribution in integral bridges.

III. BRIDGE DESCRIBTION

3.1 BRIDGE GEOMETRY

The Scotch Road Bridge, located in Trenton, NJ was chosen for this study because of (i) the abundance of field data collected, and (ii) its geometry which is a common geometry for highway FIAB. The bridge deck is 90.9 m long, divided into two 45.45 m spans, 32.91 m wide. The bridge approach slab is 6 m long, 32.91 m wide with varying thickness. The bridge has a skew angle of 14.9 degrees. The bridge abutment is 30.15 m long, 2.88 m deep and 0.9 m thick. Figure1,shows the cross section of the bridge. The bridge has six lanes, three in each direction as shown in Figure 2.

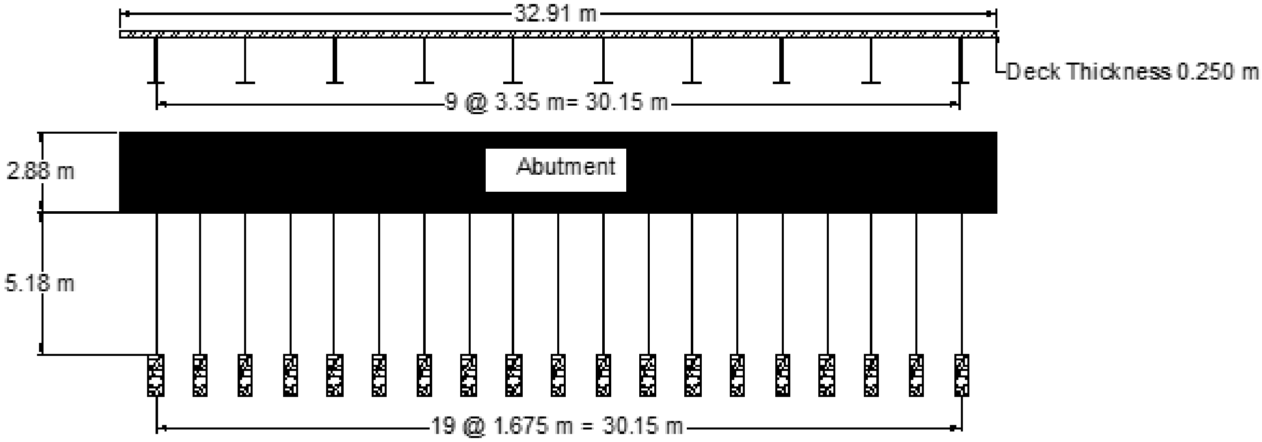


Fig.1: Scotch Road Bridge Cross sectional layout

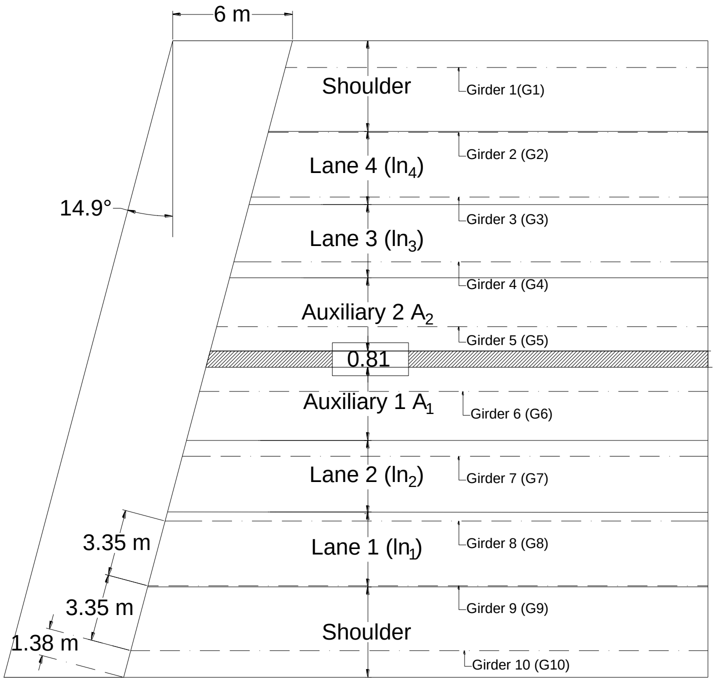


Fig.2: Scotch Road Bridge Plan View and lanes layout

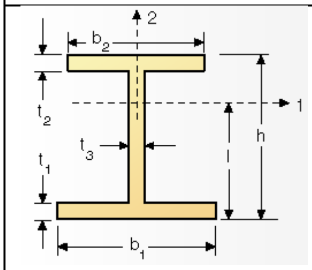
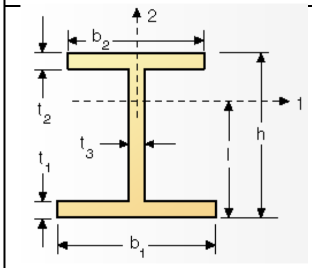
3.2 BRIDGE MATERIALS

The bridge has a 0.250 m thick reinforced concrete deck resting on steel I-beams. The deck and the abutments are rigidly connected since they were cast monolithically (Brendler, 2015). The bridge abutment is supported by steel H-piles. The abutments and the steel H-piles arerigidly connected as well. The pile length underneath soil is 5.18 m, which is well over the 4.5 m below soil depth necessary to treat the piles as fixed (Brendler, 2015). The deck and the steel girder behavior are considered elastic-perfectly plastic and modeled accordingly. The properties of the bridge materials are illustrated in Table-1. The dimensions of the steel girders and H-piles are shown in Table-2

Table.1: Materials Properties of Steel and Concrete in the Scotch Road FIAB.

Materials	Modulus of Elasticity (Mpa)	Density Kg/m^3	Coefficient of thermal expansions m/m/C^o	Poison's Ration
Steel	200	7850	0.0000117	0.3
Concrete	28.6	2400	0.0000108	0.15

Table 2Dimensions of Steel Girders and H-Piles Cross-Sections

Steel Girder	Dimensions (m)
	I=1.68 h=1.68 b1=0.6 b2=0.6 t1=0.05 t2=0.05 t3=0.022
Steel Pile	Dimensions (m)
	I=0.225 h=0.45 b1=0.39 b2=0.39 t1=0.045 t2=0.045 t3=0.022

IV. ABAQUS FINITE ELEMNET MODEL DESCRIPTION

The FE software ABAQUS/Cae was used to develop the 3D FE model of the bridge as shown in Figure 3. The deck, approach slabs and abutments were all modeled as Shell elements (S8R5). The FE model includes reinforcement to shell elements as a smeared layer embedded within the section of the elements. The piles and girders were both modeled as beam elements (B32). The model resulting from modeling the deck as a shell element and the girders as beam elements is usually referred to as a shell-beam model (SB). This approach was adopted because it reduces the model run time considerably without much effect on its efficacy (Suksawang *et al*, 2007).

Beam multipoint constraints (MPCs) were used to create the rigid link between the concrete deck and the steel girders. Using beam MPCs constrain the rotation and the displacement of the slave node to the rotation and displacement of the master node, thus mimicking the composite behavior between the deck and the girders. The deck was also rigidly connected to the abutment using MPCs. The girders and the piles were both rigidly connected to the abutment using a tie constraint. A tie constraint connects two surfaces together by not permitting any relative motion between them. It was used because it allows joining surfaces together even if they were meshed differently. A roller support was used as the boundary condition in the middle of the bridge. Figure 4, shows an undeformed shape of the FE model including applied constraints.

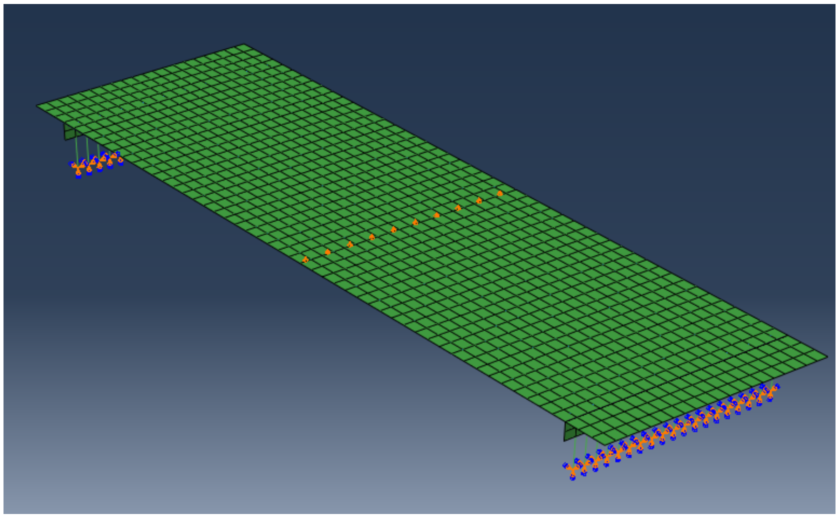


Fig.3: Undeformed Shape of theFE model of the Scotch Road Bridge using ABAQUS/Cae.

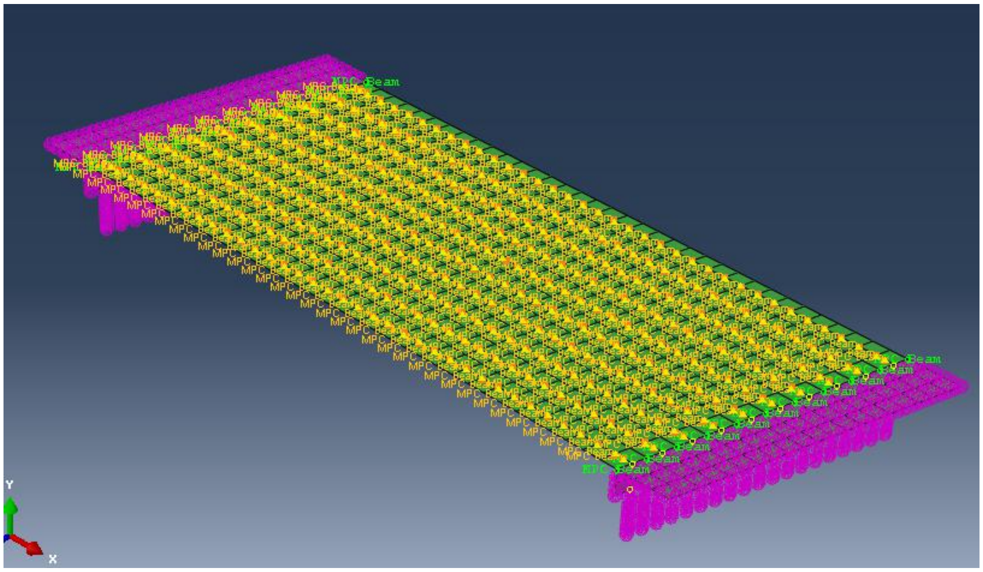


Figure 4 Undeformed Shape of the FE model with the applied constraints

V. *ABAQUS FINITE ELEMNET MODEL VALIDATION*

(Dehne *et al*, 2010) conducted a study on the Scotch Road Bridge in which he investigated the effect of seismic loading on the soil behind the abutment. As part of the study,a truck load test was performed on the bridge. The bridge was statically loaded and the resulting deflectionsfrom the truck load test recorded. To calibrate the 3D FE model used in this study, it was loaded at the same locations where the truck was positioned on the Scotch Road static truck load test and the incurred deflections were measured. The deflections of the 3D FE model were very close to those of the recorded field deflections of the actual bridge indicating its validity. Figure 5, Shows the deflections measured from the truck load test compared against the deflections measured from the 3D FE model.

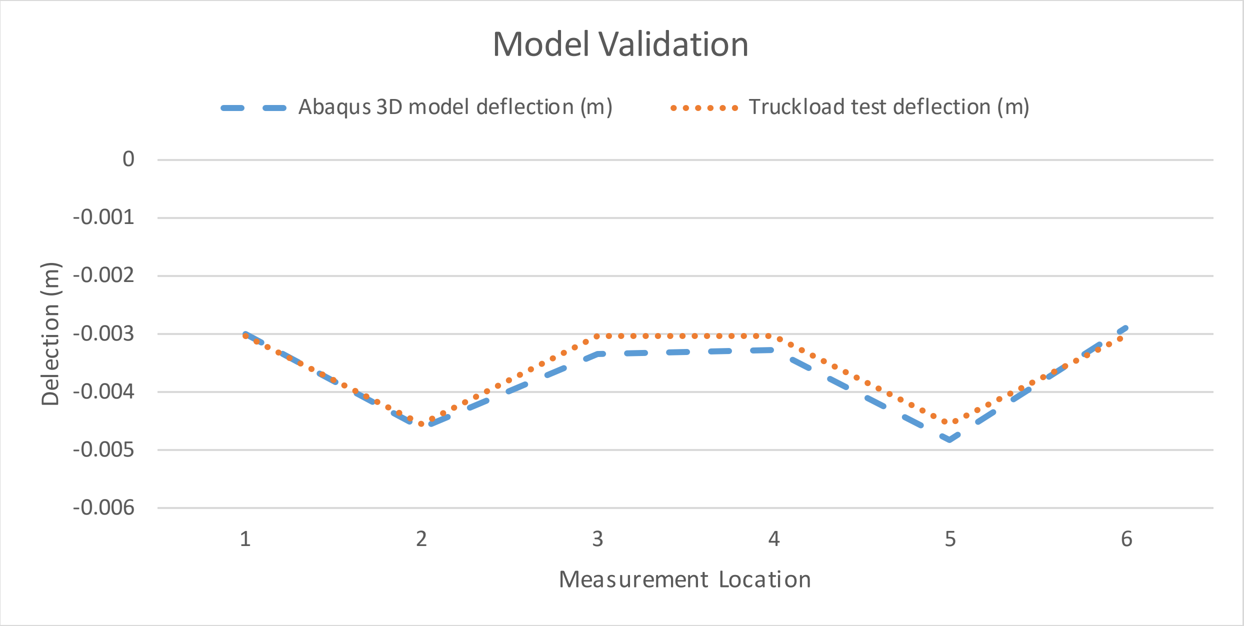


Fig.5: Comparison between measured displacements and FEM model displacements

VI. *PARAMETRIC STUDY*

The objective of this study is to evaluate the effect of different parameters on the accuracy of the AASHTO standard shear GDFs equations and the more recent AASHTO LRFD shear GDFs equations when applied to the studied IAB. The shear equations unlike the moment equations remained fairly simple with girder spacing as the primary variable used in them. The parameters shown in Table-3 were chosen to study their effect on the ASSHTO LFD and the AASHTO LRFD shear GDF equations.

AASHTO LFD equations

For 1 lane Loaded $GDF = S/2134$ *(1)*

For multiple lanes loaded $GDF = S/1676$ *(2)*

Where

$GDF = \text{Girder distribution factor}$

S = Girders spacing in (mm)

AASHTO LRFD equations

For shear in interior beams

For one lane loaded $GDF = 0.36 + S/7600$ *(3)*

For multiple lanes loaded $GDF = 0.2 + (s/3600) - (s/10700)^2$ *(4)*

For shear in Exterior beams

For one lane loaded Lever Rule (5)

For multiple lanes loaded $g = e\, g_{interior}$ (6)

$$e = .6 + d_e/3000$$

Where

$GDF = Girder\ distribution\ factor$

S = Girders spacing in mm

$g_{interior} = shear\ girder\ distribution\ factor\ for\ an\ internal\ girder.$

$d_e = horizontal\ distance\ from\ the\ centerline\ of\ the\ exterior\ web\ of\ exterior\ beam$ $at\ the\ deck\ level\ to\ the\ interior\ edge\ of\ curb\ or\ traffic\ barrier\ (mm)$

Table.3: The parameters included in the parametric study

Parameters	Parameter iterations		
	1st iteration	Original Bridge	2nd Iteration
Deck Thickness	0.200 m	0.25 m	0.300 m
Pile Length	3 m	5.18 m	8 m
Span Length	35m	45.45 m	50 m

VII. RESULTS

The 3D FE model was loaded using HS20-44 design truck as static concentrated forces in single and multiple lanes of the Scotch Road Bridge. The maximum stresses computed based on the maximum shear forces obtained from the FE model were divided by the sum of the stresses in all girders to estimate the Shear GDFs in each girder. The ratios of the shear GDFs calculated based on the results obtained from the model to those computed by AASHTO LRFD bridge design specifications and AASHTO Standard specifications were estimated to evaluate their accuracy in predicting the load to be distributed to each girder.

A limited parametric study was conducted to study crucial design parameters such as deck thickness, girder spacing and piles length. Figures (6-11) shows the ratios of the shear GDFs for each of the ten girders for one, two, and three lanes. The results show that single lane loading is most accurately predicted by the FE models, however, the shear GDFs equations for multiple lanes loading is overly conservative in both AASHTO LRFD and AASHTO Standard Specifications. Additionally, the shear GDFs factors calculated from AASHTO LRFD were greater in magnitude than those obtained from AASHTO Standard Specifications for single and multiple lanes, which indicates that AASHTO LRFD equations are more conservative in estimating the live load distribution factors for the studied integral abutment bridge. The variations between the values of the shear GDFs obtained from the FE model were 18.3, 66, and 77.2% for a deck thickness of 0.2 m, in case of AASHTO LRFD equations, while they were 11.5, 65.1, and 76.6% in AASHTO Standard Specifications. A similar trend was observed in the cases of 0.25 m, and 0.3 m deck thickness as shown in Figures 6 and 7. Furthermore, the effect of span length on the shear GDFs was studied in the Scotch Road Bridge by varying the span length to 35, and 50 m versus 45.5 m for the original bridge. Figures 8 and 9 show that the AASHTO LRFD shear GDFs equations are more conservative with a variation of 19.5, 65.5, and 77% for the case of a span length of 35 m, while they were 12.8, 64.8, and 76.4% for AASHTO Standard Specifications. A similar behavior was observed for a span length of 45.5 m (original bridge), and 50 m. The FE models were most accurate in estimating the shear GDFs for one lane loading versus multiple lanes whichhad a significantly higher margin of error. Moreover, the effect of varying the pile length on the shear GDFs ratios was also studied. The original pile length in the Scotch Road Bridge were altered to be 3 m and 8 m. The shear GDFs calculated from the AASHTO LRFD bridge design specification were greater as opposed to those computed by AASHTO Standard Specifications. The variation in the ratios were 17.9, 66, and 77.2% for AASHTO LRFD, while they were 11, 65.1, and 76.5% for AASHTO Standard Specifications indicating that AASHTO LRFD shear GDFs equations are more conservative than those of AASHTO Standard Specifications with one lane loading being the most accurate, followed by two lanes, and three lanes being the least accurate. A similar behavior was observed for the case of piles length of 5.5 m (original bridge); nevertheless, the values were almost the same for the case of 8 m as shown in Figure 10 and 11.

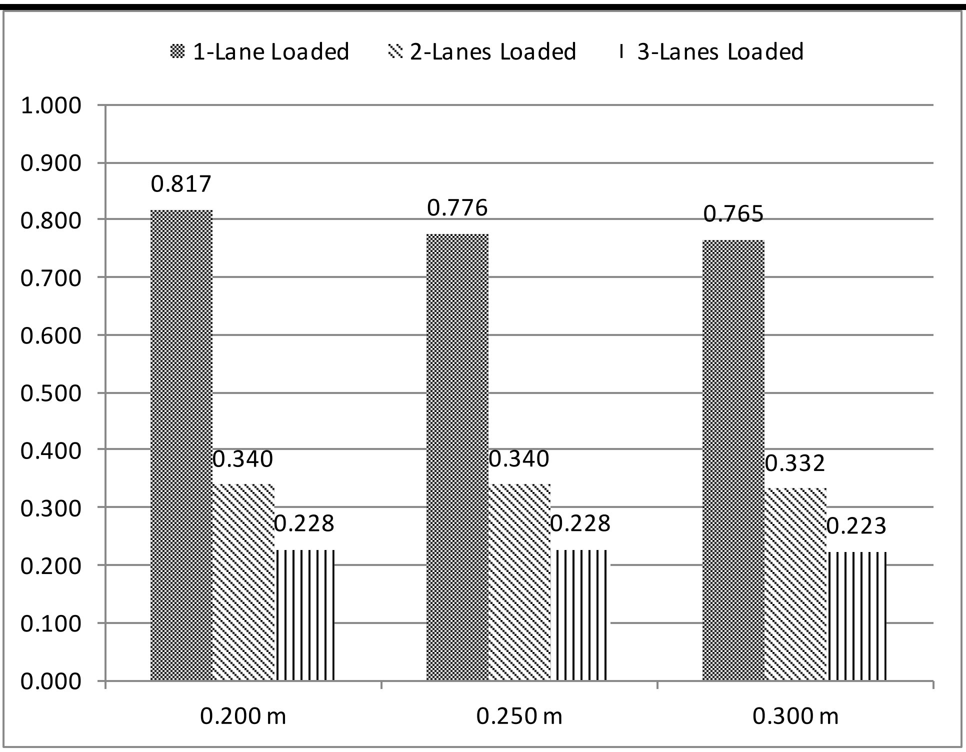


Fig.6: The GDFs ratios of the FE model to the AASHTO 2014 LRFD equations for the deck thickness parameter

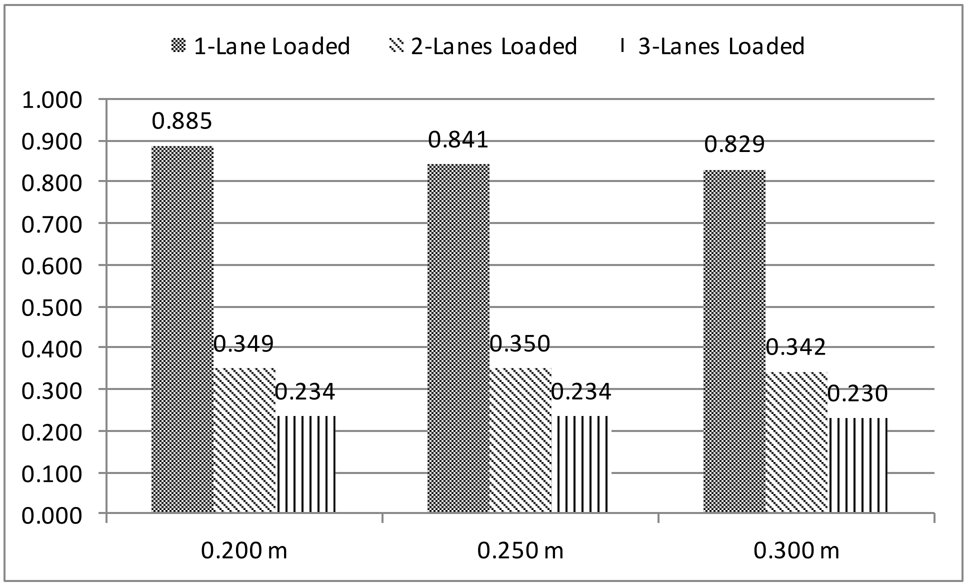


Figure 7 The GDFs ratios of the FE model to the AASHTO 1996 LFD equations for the deck thickness parameter

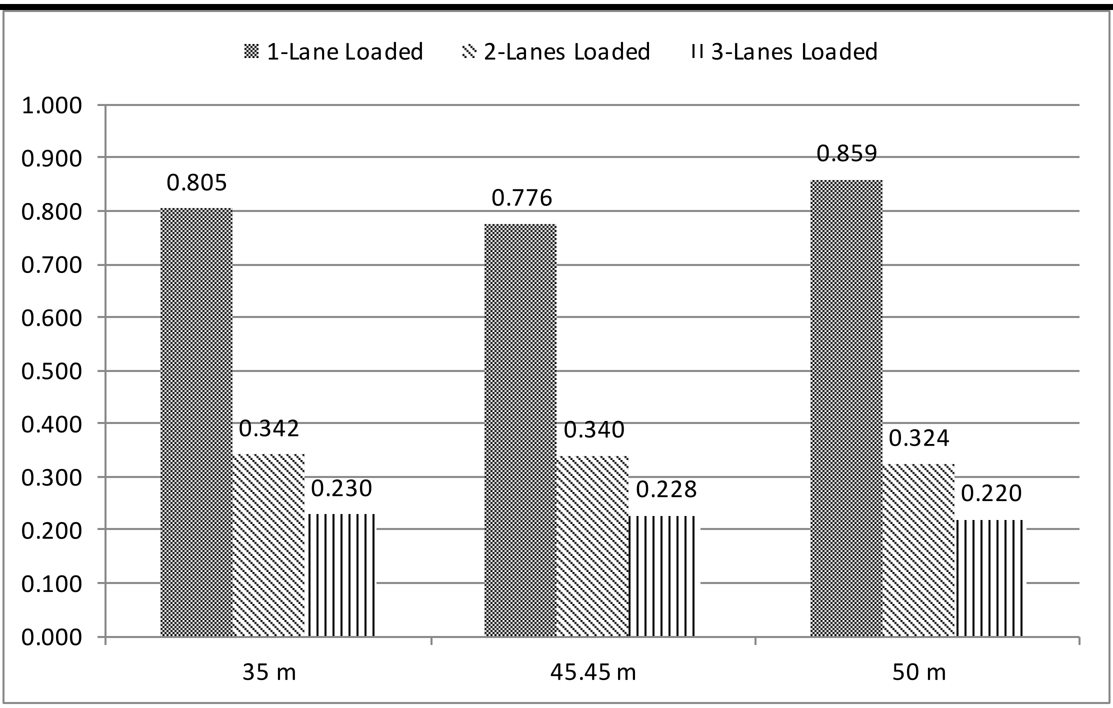


Fig.8: The GDFs ratios of the FE model to the AASHTO 2014 LRFD equations for the span length parameter

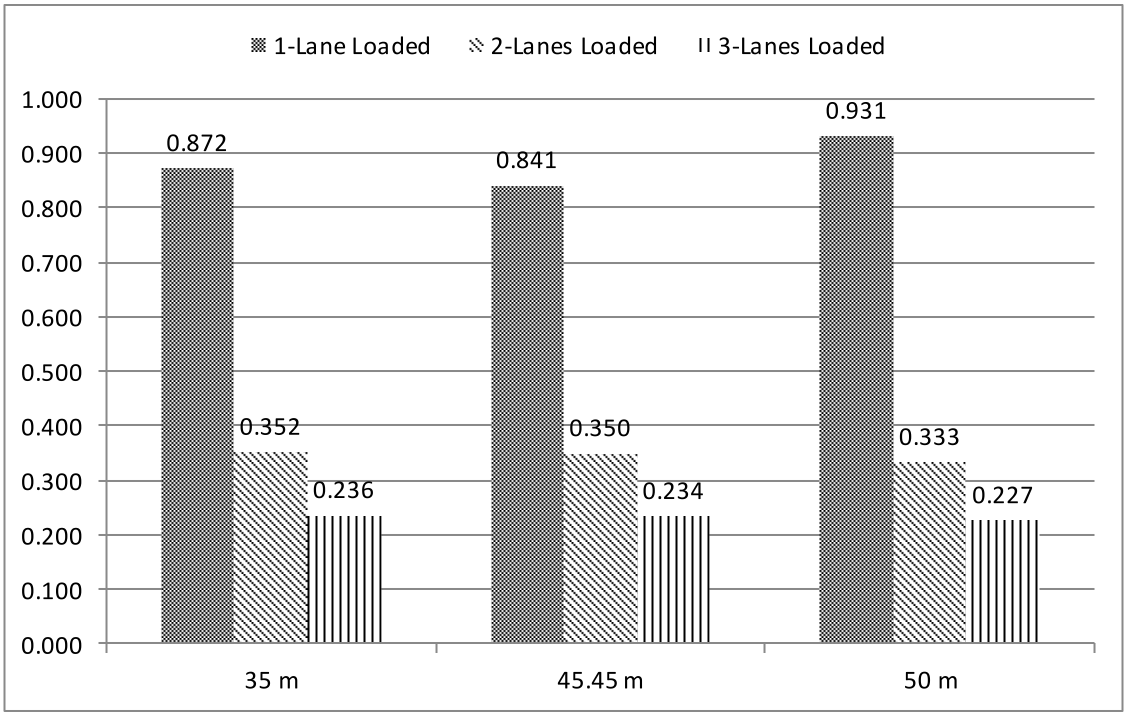


Fig.9: The GDFs ratios of the FE model to the AASHTO 1996 LFD equations for the span length parameter

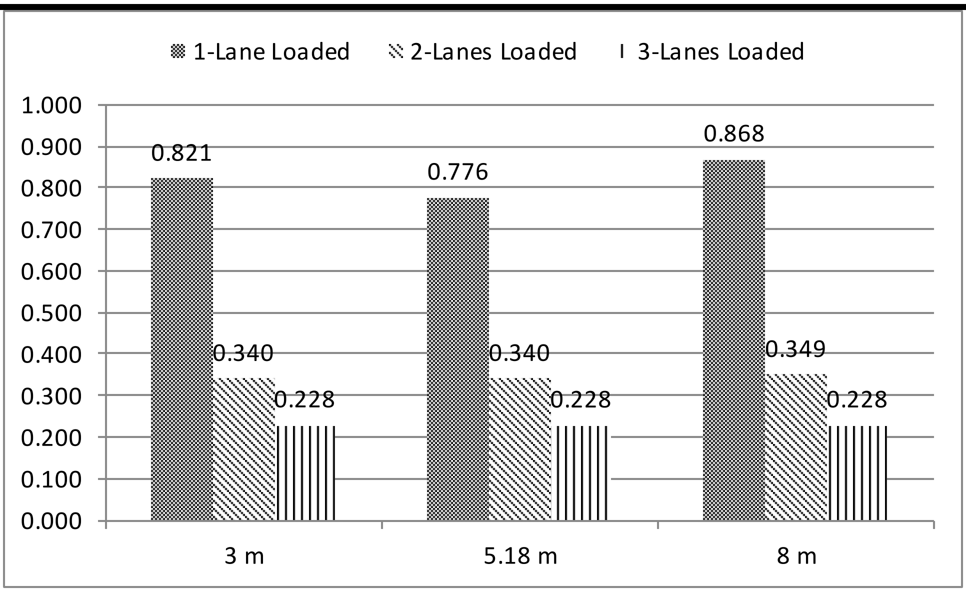


Fig.10: The GDFs ratios of the FE model to the AASHTO 2014 LRFD equations for the Piles lengths parameter

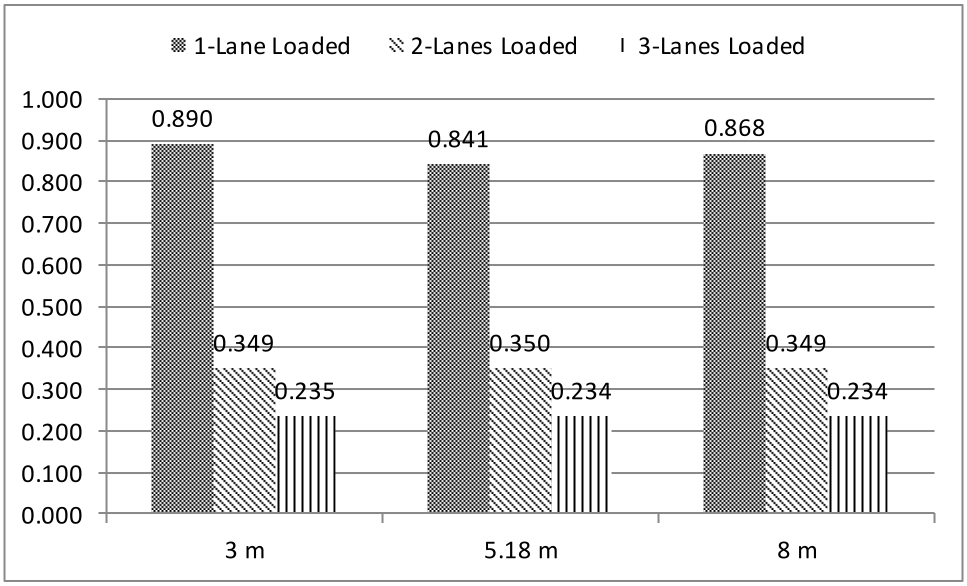


Fig.11: The GDFs ratios of the FE model to the AASHTO1996 LFD equations for the Piles lengths parameter

VIII. SUMMARY AND CONCLUISONS

The main objective of this study is to evaluate the accuracy of shear GDFs equations in AASHTO LRFD specifications versus those of AASHTO Standard Specifications using the FE method. To that end, a 3D FE model of the Scotch Road, I-95 integral abutment bridges was modelled using the finite element software Abaqus/Cae. The FE model was verified using load-displacement data due to static loading conducted by Hassiotis et al. Following the validation of the FE model, it was subject to vehicular live loading using the HS20-44 design truck in single and multiple lanes. Additionally, a limited parametric study was conducted to study the effect of crucial design parameters on the estimation of shear GDFs in the FE model. Based on the research conducted, the following can be concluded:

- The AASHTO LRFD specifications shear GDFs equations are more conservative than those adopted by AASHTO Standard Specifications.
- The shear GDFs obtained from the FE models for one lane loading are closer in value to those calculated based on both design codes as opposed to multiple lane loading.

- Changing the deck thickness has a significant effect on the shear GDFs in the studied integral bridge for single and multiple lanes.
- Changing the span length has a significant effect on the shear GDFs in the studied integral bridge for single and multiple lanes.
- Changing the span length has a significant effect on the shear GDFs in the studied integral bridge for single and multiple lanes. However, increasing the length of the piles to 8 m didn't result in a significant change in the shear GDFs ratios.
- Both AASHTO Standard Specifications and AASHTO LRFD Specifications are more conservative in predicting shear GDFs with one lane loading being the most accurate versus using multiple lanes.

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