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Live Load Distribution for Steel-Girder Bridges

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Abstract

Grillage method is used here to determine girder distribution factor (GDF). STAAD Pro. 2006 program is used here to represent grillage and solving for (GDF). Different GDFs are adopted by AASHTO LRFD based on the National Cooperative Highway Research Program (NCHRP) 12-26 and the results compared with formulas given by AASHTO Standard. Three different composite steel bridge superstructures are considered with girder spacing (1.22, 2.44 and 3.66 m). To compute GDF in the considered bridges subjected to one truck, the vehicle is placed on each bridge such that the load effect in the girders is maximized. If compared with Finite element method, the modified grillage was found to be simple, efficient and having practical accuracy in the analysis of bridge decks in determining GDF factors.

Keywords: grillage, composite bridges, GDF, AASHTO

توزيع الاحمال الحية للروافد الفولاذية الجسرية

الخلاصة

تم استخدام طريقة المشبكات لايجاد معامل التوزيع للروافد GDF. تم استخدام برنامج STAAD Pro. 2006 لتمثيل المشبك و لايجاد GDF. معاملات مختلفة تم تبنيها من قبل AASHTO LRFD اعتمادا على دراسة NCHRP و تم استخدام صيغ مختلفة عن AASHTO Standard. ثلاثة أنواع مختلفة من الجسور المركبة أخذت بنظر الأعتبار ذات فضاءات بين العتبات مختلفة (1,22, 2,44 و 3,66 م). لأيجاد GDF في الجسور محل الدراسة معرضة لحمل مركبة متغيرة تم تحديد موقع المركبة لتعطي أكبر نسبة من الأحمال على العتبات المكونة للجسر. وقد أثبتت طريقة المشبكات المعدلة لتحليل بلاطات الجسور إنها طريقة بسيطة, كفوءة, وذات دقة جيدة للأغراض التطبيقية و خاصة في ايجاد نسبة GDF بالمقارنة مع طريقة العنلصر المحددة.

Introduction

The current demands of society and industry occasionally require a truck to carry a load that exceeds the size and weight of the legal limit. In these cases, engineering analysis is required before a permit is issued to ensure the safety of the structures and roadways on the vehicle's route. Truck size and weight requirements have been motivated by concerns for national uniformity and effective highway system administration [1]. Over the years, new bridge design specifications and standards have been adopted to better match the sizes and weights of vehicles permitted to operate on the highway networks. The limitation of

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vehicle size and weight is based on pavement and bridge capacity. A truck with a wheel gauge larger than the standard 1.83 m (6 ft) gauge requires additional engineering effort because the wheel load girder distribution factors (GDFs) established by AASHTO cannot be used to accurately estimate the live load in the girders.

Many techniques are available to determine transverse load distribution. According to Ref. [2], Zokaie et al. (1991) grouped analytical techniques into two different levels of analysis from detailed modeling to simplified equations. Field testing can also provide information on load distribution for a given bridge type and geometry. According to Ref. [2], Kim and Nowak (1997) determined GDFs from field measurements using Eq. (1)

$$\mathrm{GDF}_{\mathrm{i}} = \frac{e_{\mathrm{i}}}{\sum e_i} \qquad \text{..... (1)}$$

where ε_i = maximum static strain in the *i*th girder.
$\sum\varepsilon_i$ = summation of the static strains in all girders.

Live Load Distribution Factors

In bridge design and evaluation specifications, the distribution of truck loads on slab-on-girder bridges is usually accomplished using a girder distribution factor (GDF) that defines the percentage of live load carried by one girder. This factor simplifies the girder design by providing an approximate procedure for distributing the live load in bridges without a detailed analysis. In the National Cooperative Highway Research Program (NCHRP) 12-26 method which was adopted by AASHTO LRFD [3], the wheel load GDF for the case of flexure in an interior girder in a simply supported bridge subjected to one loaded lane is given by [1]

$$\mathrm{GDF} = 0.1 + \left(\frac{S}{1.22}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{K_g}{L.t_S^3}\right)^{0.1} \qquad \text{….. (2)}$$

The corresponding expression for bridges with two or more loaded lanes is

$$\mathrm{GDF} = 0.15 + \left(\frac{S}{0.915}\right)^{0.6}\left(\frac{S}{L}\right)^{0.2}\left(\frac{K_g}{L.t_S^3}\right)^{0.1} \qquad \text{….. (3)}$$

where
S = girder spacing (m).
L = span length of bridge (m).
t_S = slab thickness (m).

The longitudinal stiffness parameter K_g accounts for the effect of the girder stiffness on the live load distribution characteristics of the bridge and is defined as

$$K_g = n\left(I_g + A_g e_g^2\right) \qquad \text{.... (4)}$$

where
n = modular ratio between the girder and slab.
I_g = moment of inertia of the girder (m^4).
A_g = cross-sectional area of the girder (m^2).
e_g = distance from the geometric center of the girder to the middepth of the slab (m).

The shear GDF for an interior girder with one loaded lane can be obtained from the following equation [4]:

$$\text{GDF} = 0.6 + \frac{S}{4.58} \quad ....(5)$$

The corresponding expression for a bridge with two or more loaded lanes is

$$\text{GDF} = 0.4 + \frac{S}{1.83} - \left(\frac{S}{7.63}\right)^2 \quad ....(6)$$

The GDF expressions in (2) to (6) have been developed based on an HS20-44 truck configuration that has a gauge width equal to 1.83 m (6 ft). They also include multiple presence factors based on the AASHTO standard bridge design specifications [4].

For the case of an exterior girder subjected to one loaded lane, the lever rule is used. For the corresponding case with two or more loaded lanes, the following equation is used to determine the GDF for the exterior girders $(\text{GDF})_{\text{Ext}}$ in terms of the GDF for the interior girder $(\text{GDF})_{\text{Int}}$ [1]:

$$(\text{GDF})_{\text{Ext}} = e*(\text{GDF})_{\text{Int}} \quad ...(7)$$

where
e^* = (2.14 + d_e)/2.78 for the case of flexure and (1.83 + d_e)/3.05 for the case of shear, in which d_e is the edge distance of traffic lanes (m), defined as the distance between the center of the outside roadway stringer web to the edge of the exterior lane.

Truck Models

Four overweight, oversized truck models are considered in this study. They include the AASHTO HS20-44 design truck, Pennsylvania DOT's (PennDOT's) P-82 permit truck (PennDOT 1993), Ontario Highway Bridge Design Code's (OHBDC's) load level 3 truck (OHBDC 1992), and HTL-57 national truck, Federal Highway Administration (FHWA 1994) [1]. The four trucks differ from each other in the number of axles, axle spacing, gross weight, and axle weight. With the exception of the HS20-44 truck, these vehicles represent trucks that would normally require a permit for routes including bridge crossings. The HS20-44 truck is 8.6 m long, weighs 320 kN (72 kips), and consists of three axles that are spaced at 4.27 m (14 ft). The P-82 permit truck has a wheelbase of 17 m and includes eight axles with a total weight equal to 907 kN (204 kips). The OHBDC truck has five axles with a wheelbase equal to 18 m and a GVW (Gross Vehicle Weight) of 740 kN (166 kips). Finally, the HTL-57 truck is 15.3 m long and includes six axles with a gross weight of 505 kN (114 kips). The configurations of the considered trucks are shown in Figure (1). For the most critical truck, wheel gauges of 1.83, 2.44 and 3.05 m (6, 8 and 10 ft) are considered in the live load analysis, as shown in Figure (2).

Critical Parameters

In this section, the critical interior girder and critical truck configuration for live load distribution in simply supported, slab-on-girder bridges are determined. To compute the GDF in the considered bridges subjected to one truck, the vehicle is placed on each bridge such that the load effect in the girders is maximized. The longitudinal truck position for maximum flexure at midspan or maximum shear at the support can be easily determined using influence lines for simply supported beams. The critical transverse location of the truck can be found by examining the stress in the bottom flange of each steel girder for the case of flexure, or the support reaction of each steel girder for the case of shear, for different transverse truck positions *X*, where *X* is defined in Figure(3) [1]. Note that when the left wheel of a truck is on the deck overhang, the dimension *X* is negative.

Bridges Considered

Three different composite steel bridge superstructures are considered. One superstructure is composed of a 150 mm (6 in.) thick slab on seven steel beams spaced at 1.22 m (4 ft) considered as (Bridge I), another consists of a 200 mm (8 in.) thick slab on five steel beams spaced at 2.44 m (8 ft) considered as (Bridge II), and a third includes a 250 mm (10 in.) thick slab on four steel beams spaced at 3.66 m (12 ft) considered as (Bridge III), as shown in Figure (4). For each bridge layout, simple span length is 29.3 m (96 ft). For the 2.4 m (8 ft) girder spacing, the rolled steel beam cross section is W920×446 (W36×300) for the 29.3 m (96 ft) span. The web depth of the rolled steel beam used with the 2.4 m (8 ft) girder spacing is decreased by 300 mm (12 in.) for the 1.2 m (4 ft) girder spacing and increased by 300 mm (12 in.) for the 3.6 m (12 ft) girder spacing. The deck slab overhang is taken to be equal to half the girder spacing. A summary of the superstructure geometry for the considered bridges as well as details of properties are tabulated in Tables (1) and (2). The bridge configurations chosen reflect a reasonable range of parameters used in slab-on-girder bridges.

Bridge I

First bridge considered is bridge I. The modified grillage mesh which was adopted for the analysis consists of "735" nodes represented by "15" transverse nodes in "49" longitudinal rows equally spaced along the bridge span as shown in Figure (5) and total number of beams is "2750".

The equivalent rigidities of the main beams (λ=610 mm, $k\lambda$=610 mm) of the test deck $(EI)_x$, $(EI)_y$, $(GJ)_x$, $(GJ)_y$ and $(EI)_d$ needed for the analysis are calculated using formulas given in Ref. [5] and they are given in Table (3). The flexural and torsional rigidities of the equivalent orthotropic plate (D_x, D_y, D_{xy} and D_{yx}) needed for analysis are calculated using formulas which were suggested by Flaih [6].

Flexural GDFs of bridge I subjected to one loaded lane of the AASHTO standard specifications (4) and the NCHRP 12-26 study [3] gives 0.580 and 0.486 respectively, while shear GDF of bridge I subjected to one loaded lane gives 0.785 and 0.866 respectively.

Bridge II

Second bridge considered is bridge II. The modified grillage mesh which was adopted for the analysis consists of "275" nodes represented by "11" transverse nodes in "25" longitudinal rows equally spaced along the bridge span and total number of beams is "994".

Dimensions of the beams in *x* and *y*-direction are λ=1220 mm, $k\lambda$=1220 mm, respectively. Flexural and torsional rigidities for this bridge deck are tabulated in Table (3). Flexural GDFs of bridge II subjected to one loaded lane of the AASHTO standard specifications [4] and the NCHRP 12-26 study [3] gives 1.133 and 0.730 respectively, while shear GDF of bridge I subjected to one loaded lane gives 1.200 and 1.133 respectively.

Bridge III

Third bridge considered is bridge III. The modified grillage mesh which was adopted for the analysis consists of "153" nodes represented by "9" transverse nodes in "17" longitudinal rows equally spaced along the bridge span and total beam "536".

Dimensions of the beams in x and y-direction are λ=1830 mm, $k\lambda$=1830 mm, respectively. Flexural and torsional rigidities for this bridge deck are tabulated in Table (3). Flexural GDFs of bridge III subjected to one loaded lane of the AASHTO standard specifications [4] and the NCHRP 12-26 study [3] gives 1.510 and 0.932 respectively, while shear GDF of bridge I subjected to one loaded lane gives 1.540 and 1.400 respectively.

Critical Interior Girder

In all cases considered, the first interior girder was found to be the most critical interior girder in both flexure and shear. Figures (6) and (7) show the flexural GDF versus the transverse truck position for the interior girders of bridge (I and II) with 1.22 m (4 ft) and 2.44 m (8 ft) girder spacings, respectively. The corresponding results for the shear GDF are shown in Figures (8) and (9). Also shown in Figures (6) through (9) are the GDFs that are based on the AASHTO standard specifications [4] and the NCHRP 12-26 study [3]. The girder numbering scheme is shown in Figure (4). The results are shown for bridges subjected to a single HS20 truck with a gauge width of 1.83m.

Critical Truck Configuration

The four different truck types that are used for evaluating the live load distribution in the bridges considered are the HS20, OHBDC, PennDOT P-82, and HTL-57. The axle spacings and weight distribution of the four trucks are shown in Figure (1), and the gauge for each is taken equal to 1.83 m (6 ft). Each of the trucks is positioned on the bridges such that the moment in the first interior girder is maximized at midspan or shear in the same girder is maximized at the support. Figures (10) and (11) present the flexural GDF results for bridge (I and III) with 1.22 m (4 ft) and 3.66 m (12 ft) girder spacings. The corresponding GDF results for shear in the same bridges are shown in Figures (12) and (13).

Effect of Larger Gauge Widths

The applied loading consists of a single HS20 truck with 1.83, 2.44 and 3.05 m gauge widths as shown in Figure (2). Figures (14) and (15) present typical results for the flexural and shear GDF in the first interior girder of bridge II (a 29.3 m long bridge with five girders spaced at 2.44 m).

Discussion of Results

This study focuses on the distribution of live load to interior girders in slab-on-girder bridges due to one loaded traffic lane. Figures (6) through (9) show the flexural and shear GDF versus the transverse truck position for the interior girders of bridges I and II. Also shown in Figures (6) to (9) are the GDFs that are based on the AASHTO standard specifications [4] and the NCHRP 12-26 study [3]. Note that the standard AASHTO GDF shown for shear is a composite factor because the axles near the support have a different GDF than the axles located away from the support. Because of the symmetry of the bridge superstructure, interior girders equally spaced from the bridge centerline have GDF influence lines that are mirror images of each other. Therefore, only unique transverse influence line diagrams for the girders are shown in Figures (6) to (9). For the same reason, the bridge with the 3.66 m (12 ft) girder spacing is not considered because it only has four girders, of which the two interior girders are similar. Although the results are shown for bridges subjected to a single HS20 truck with a gauge width of 1.83 m (6 ft), the first interior girder was consistently the most heavily loaded girder when the bridges were subjected to other truck configurations and different gauge widths. Figures (6) through (9) also indicate that the NCHRP 12-26 factors are better predictors of the GDF for flexure, whereas the factors in the AASHTO standard specifications are better predictors of the GDF for shear for the bridge configurations considered in this study.

Figures (10) through (13) show that the HS20 truck configuration produces the largest GDF for both flexure and shear. Furthermore, the HS20 truck is more critical than the other vehicles for shear than for flexure. This result is expected because the HS20 truck has the fewest axles and the shortest wheelbase among the four considered trucks. Structural analysis of the bridges subjected to trucks having gauges other than 1.83 m produced the same conclusions. The results also indicate that the NCHRP 12-26 factors can predict the GDF for flexure better than the factors included in the AASHTO standard specifications. The opposite is true for the case of shear for the bridge configurations considered.

Figures (14) and (15) present typical results for the flexural and shear GDF in the first interior girder. The results indicate that the GDF decreases with an increase in gauge. Furthermore, the transverse truck position for maximum GDF, *X* is different for the various gauge widths considered.

The results show that an increase in the gauge from 1.83 to 3.05 m can lead to a reduction of up to 5.22% in the GDF value for flexure. The decrease in the GDF for shear when the gauge increases from 1.83 to 3.05 m can be as high as 36.93%.

Furthermore, the reduction in the GDF is mainly a function of the gauge width and girder spacing. The span length has a minor effect on the modified GDF due to a change in the gauge width. For the case of flexure, the gauge of a vehicle influences the live load distribution in bridges with small girder spacings more than in bridges with large girder spacings. On the other hand, for the case of shear, bridges with moderate and large girder spacings are affected by a change in gauge width more than bridges with small girder spacings.

Conclusions

Based on the results of this study, the following conclusions are relevant for slab-on-girder bridges:

1. The HS20-44 truck has the most critical GDF among the four overweight trucks that are considered in the study.
2. The first interior girder receives the largest percentage of live load among the interior girders of the three bridges considered. The transverse truck position for maximum load effect in the critical interior girder is usually different for shear than for moment.
3. GDFs for interior girders in slab-on-girder bridges are lower for oversized trucks than for standard trucks with 1.83 m (6 ft) gauge width.
4. The reduction in the GDF for interior girders due to a vehicle with a large gauge is different for flexure than for shear. Gauge width affects shear due to live load more than it affects flexure.

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[2] Schwarz, M. and Jeffrey, A. L., "Response of Prestressed Concrete I-Girder Bridges", Journal of Bridge Engineering, ASCE, February 2001.

[3] American Association of State Highway and Transportation Officials (AASHTO), (1998), Washington, D.C.

[4] American Association of State Highway and Transportation Officials (AASHTO), (1996), Standard specifications for highway bridges, Washington, D.C.

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[6] Flaih, R. H., "Bridge Deck Analysis using Orthotropic Plate Theory", M. Sc. Thesis Presented to the University of Technology, 2005.

Table (1) Parameters of Bridge Geometry [1]

Bridge	Span length (m)	Girder spacing (m)	Slab thickness (mm)	Flange thickness (mm)	Flange width (mm)	Web thickness (mm)	Web depth (mm)
I	29.3	1.22	150	43	423	24	548
II	29.3	2.44	200	43	423	24	848
III	29.3	3.66	250	43	423	24	1148

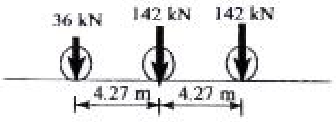
Table (2) Properties of Considered Bridges

Type of Properties	Value
Modular ratio (*n*)**	9
Beam Elastic Modulus	$2*10^5$ MPa
Concrete Poisson's ratio	0.18

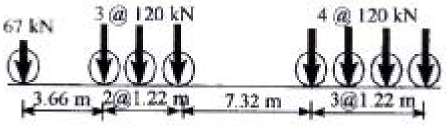
** $n=E_s/E_c$

Table (3) Main Properties of Bridge Beams using Modified Grillage Method ($N.mm^2$)

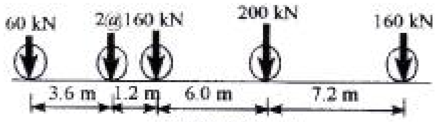
Type of Rigidities	Bridge I	Bridge II	Bridge III
$(EI)_x$	$4.919287409*10^{14}$	$1.319191863*10^{15}$	$2.67591385*10^{15}$
$(EI)_y$	$1.563321165*10^{12}$	$7.412013093*10^{12}$	$2.17170189*10^{13}$
$(EI)_d$	$9.706258512*10^{11}$	$4.601928047*10^{12}$	$1.348353775*10^{13}$
$(GJ)_x$	$6.695014447*10^{13}$	$2.076809851*10^{14}$	$4.67630688*10^{14}$
$(GJ)_y$	$6.695014447*10^{13}$	$2.076809851*10^{14}$	$4.67630688*10^{14}$



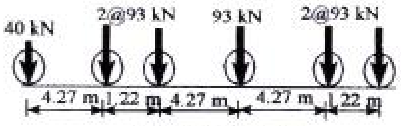
(a) HS20-44 Truck



(b) PennDOT P-82 Permit Truck



(c) OHBD Truck



(d) HTL-57 Truck

Figure (1) Truck Configurations Considered in Study.

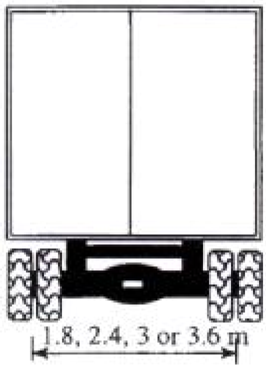


Figure (2) Gauge Widths Considered in Study.

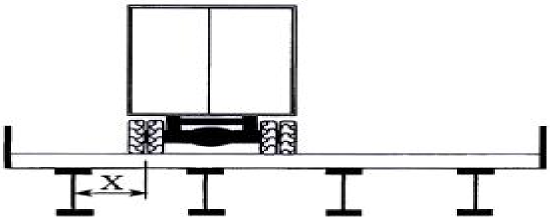
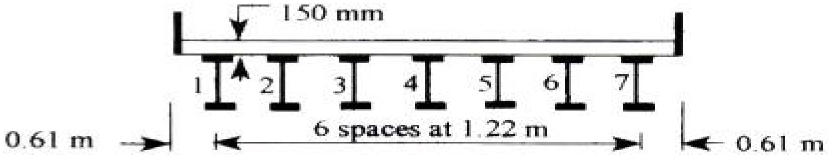
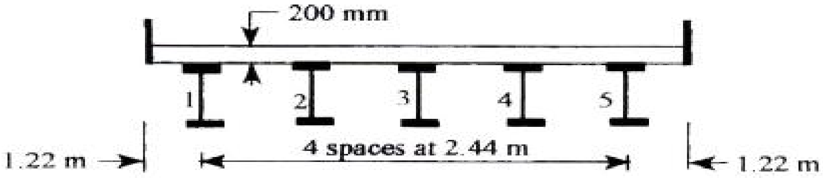


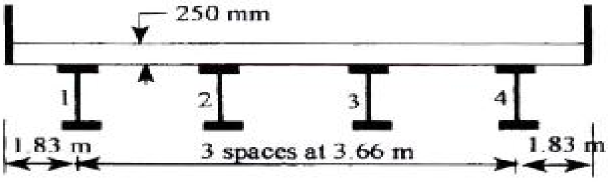
Figure (3) Definition of Distance *X*.



(a)Bridge I with 1.22 m Girder Spacing.



(b) Bridge II with 2.44 m Girder Spacing.



(c) Bridge III with 3.66 m Girder Spacing.

Figure (4) Bridge Layouts Considered in Study.

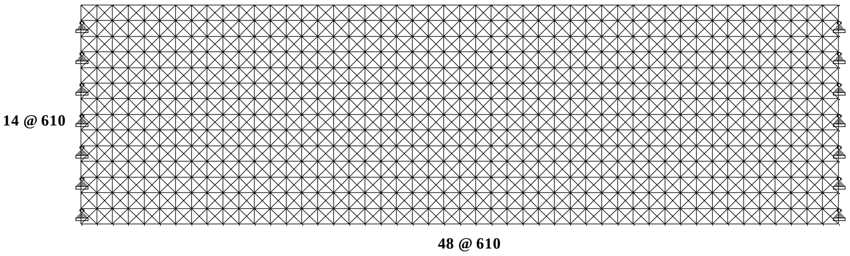
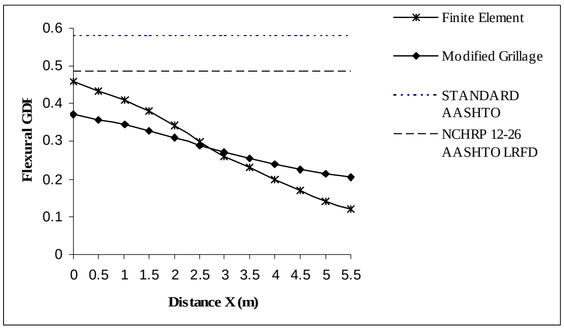
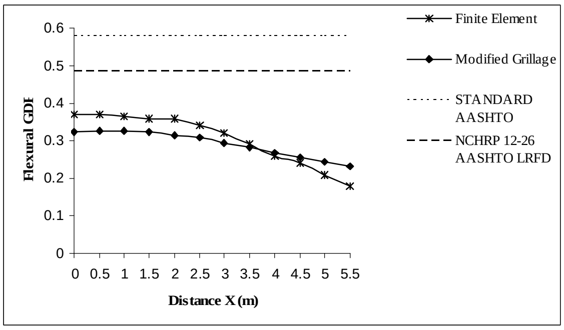


Figure (5) Bridge I by Modified Grillage.

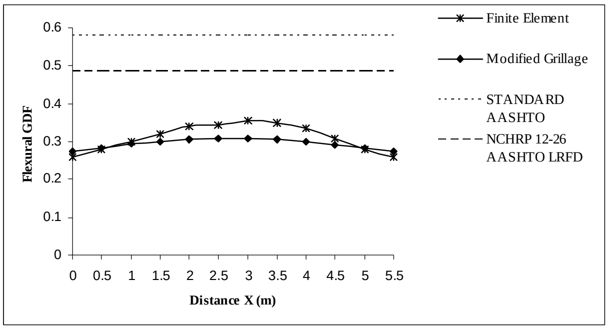


(a)Flexural GDF of Girder 2.



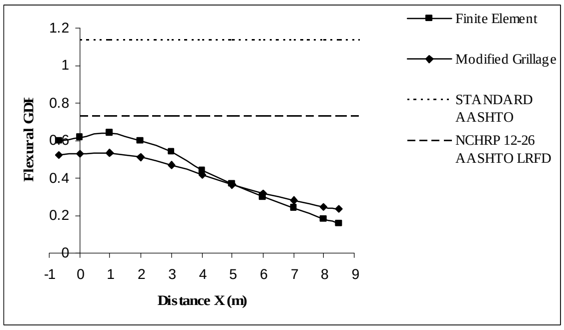
(b) Flexural GDF of Girder 3.

Figure (6) Determination of Critical Interior Girder in Flexural for Bridge I.

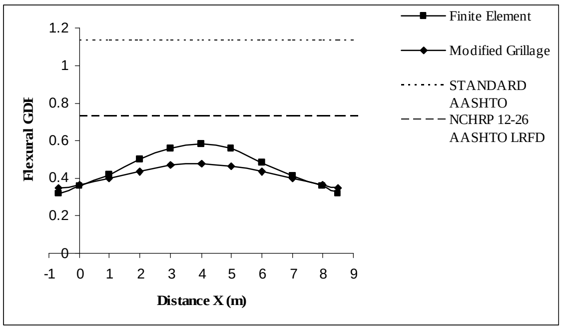


(c) Flexural GDF of Girder 4.

Figure (6) Continued.

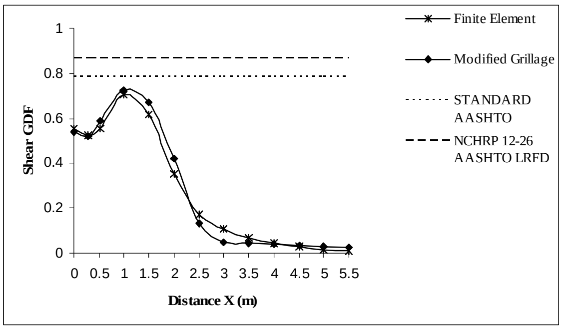


(a)Flexural GDF of Girder 2.

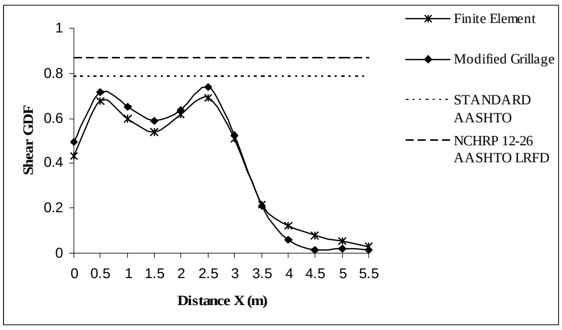


(b)Flexural GDF of Girder 3

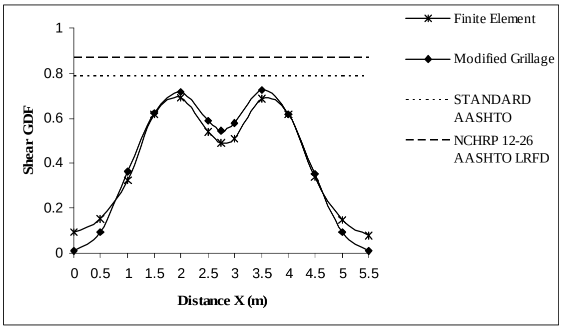
Figure (7) Determination of Critical Interior Girder in Flexural for Bridge II.



(a)Shear GDF of Girder 2.

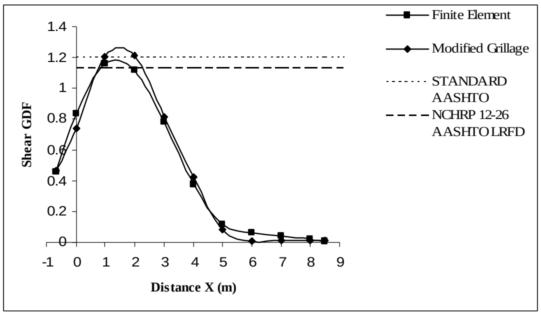


(b)Shear GDF Girder 3.

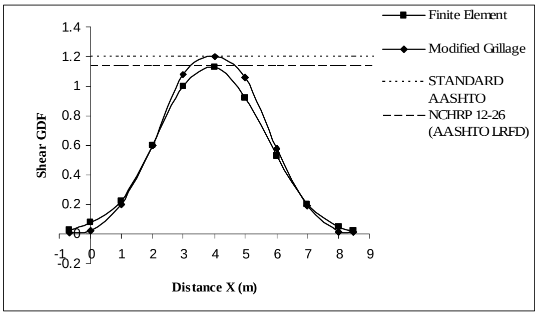


(c)Shear GDF Girder 4.

Figure (8) Determination of Critical Interior Girder in Shear for Bridge I.

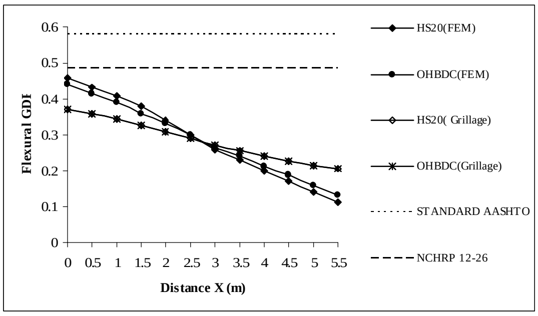


(a)Shear GDF of Girder 2.



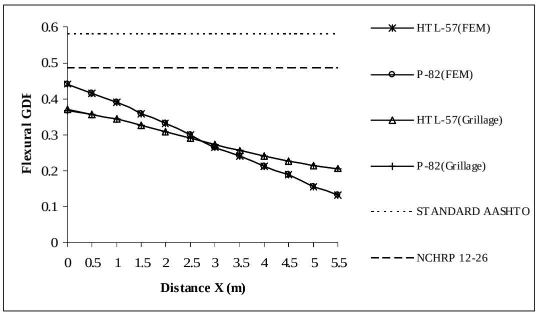
(b)Shear GDF of Girder 3

Figure (9) Determination of Critical Interior Girder in Shear for Bridge II.



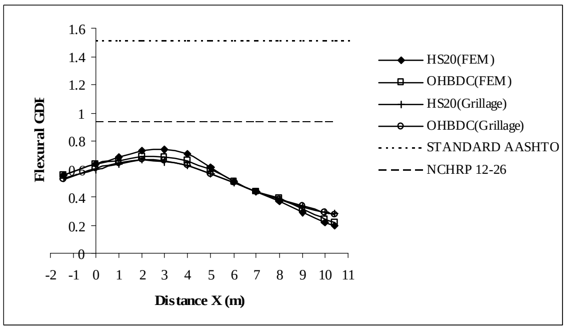
(a)

Figure (10) Determination of Critical Truck Configuration for Case of Flexure in Bridge I.

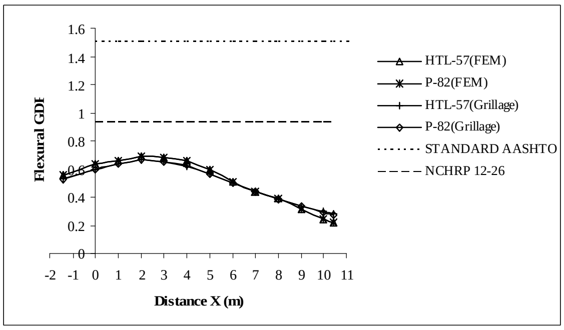


(b)

Figure (10) Continued.

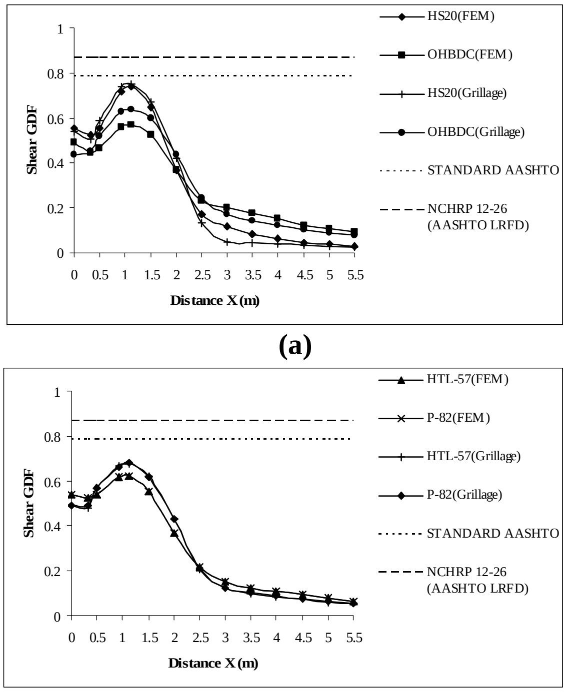


(a)



(b)

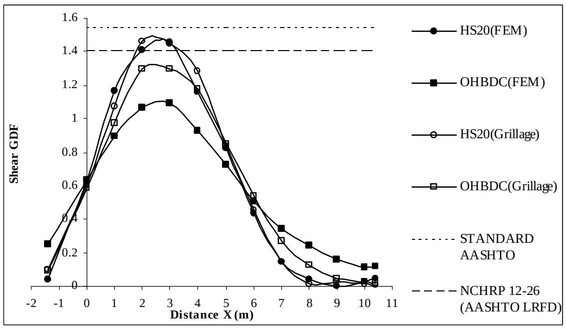
Figure (11) Determination of Critical Truck Configuration for Case of Flexure in Bridge II.



(a)

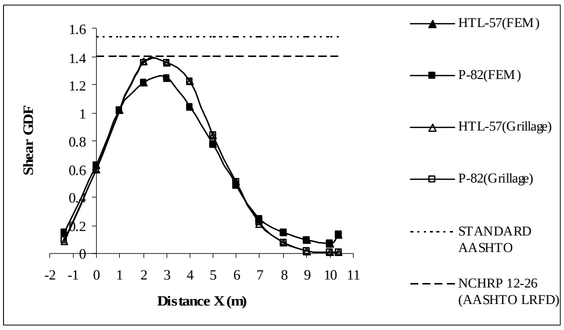
(b)

Figure (12) Determination of Critical Truck Configuration for Case of Shear in Bridge I.



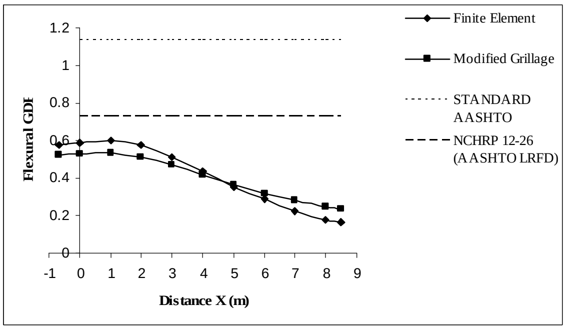
(a)

Figure (13) Determination of Critical Truck Configuration for Case of Shear in Bridge III.

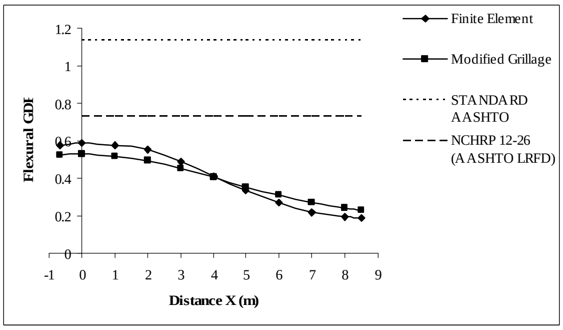


(b)

Figure (13) Continued.

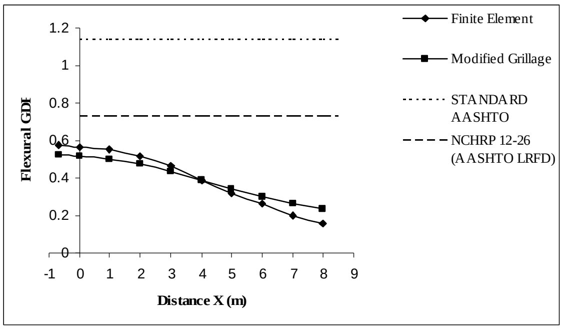


(a) Gauge 1.83 m



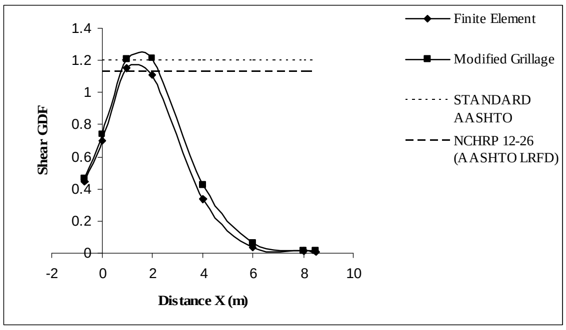
(b) Gauge 2.44 m

Figure (14) Effect of Gauge on Flexural GDF for Bridge II with 2.44 m Girder Spacing.

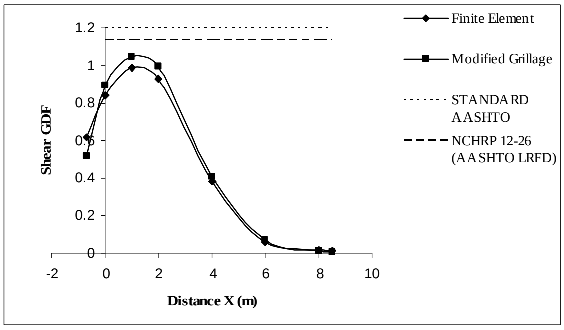


(c) Gauge 3.05 m

Figure (14) Continued.

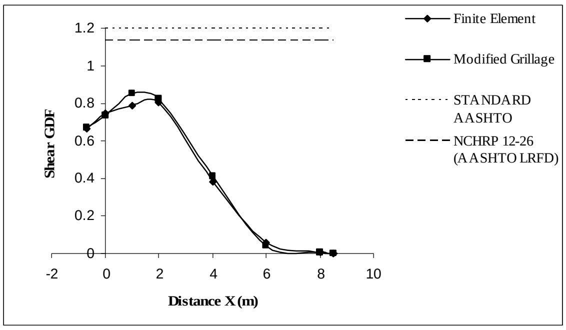


(a) Gauge 1.83 m



(b) Gauge 2.44 m

Figure (15) Effect of Gauge on Shear GDF for Bridge II with 2.44 m Girder Spacing.



(c) Gauge 3.05 m

Figure (15) Continued.