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Live Load Distribution of Prestressed Concrete Girder Bridge with Curved Slab

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Abstract

The existing AASHTO Standard Specification have some inadequacies in expressing wheel load distribution of bridge which has specific shape of curved bridge instead of straight bridge. Thus, this research presented the finite element analysis and modelling technique of prestressed concrete girder bridge having curved slab and the expression of wheel load distribution was suggested as the ratio of bending moment utilizing the result of finite element analysis of prestressec concrete girder bridge having curved slab. The considered parameter of girder distribution expression is the curvature of slab, span length, girder space, cross beam space and number of lanes. Though the suggested girder distribution expression is generally underestimated below AASHTO Standard Specification, once the curvature of slab increases, the suggested expression gets larger than AASHTO LRFD[5)] Standard Specification.

Keywords: wheel load distribution, finite element analyses, PSC-beam bridges, curved slab

1. Introduction

In case that bridge is located at the curved part of linear road, the bridge is usually planned to be curved bridge in consideration of functional aspect to facilitate traffic or aesthetic appearance. To augment convenience and promptness in construction and lessen the influence of distortion, in the case of prestresed concrete girder bridge around urban area, girders are constructed in prefabricated straight line and slab, in curved line.

Because of the improved function of computer program in recent days, very efficient and exact technique is suggested in analyzing bridges. However, an analysis technique that exactly reflects the influence of the curvature of slab is not yet definitely presented for prestressed concrete girder bridge with curved slab and the overall bridge is modelled in straight grillage element merely because it is simple for design or structural analysis.

As a matter of fact, prestressed concrete girder bridges with curved slab constructed recently have cracks at bottom flange of exterior girder, which increase the demand of repair and reinforcement. As a cause of these cracks, modelling technique can be enumerated, which fails to effectively convey the influence of curvature of slab to girder when wheel load passes by modelling the overall bridge in grillage element for analyzing existing design or structure.

Utilizing finite element analysis that provides complicated structural analysis with effective means to form analysis model to exactly grasp the actual reaction of prestressed concrete girder bridge with curved slab and considering girder space, span length, curvature of slab and number of lane, etc. which affect considerably girder distribution as parameters, this dissertation will suggest rational girder distribution factor (GDF). In addition, GDF with which the existing AASHTO Standard Specification can solve problems such as excessive design, etc. that can occur in the bridge with curved slab will be suggested.

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2. The specification and application of existing girder distribution factors

2.1 Girder distribution factors : GDFs

Up to now, many methods have been suggested to determine the wheel GDF on the bridge. Zokaie[14] defined standard to induce simple expression from detailed bridge model and the GDF for lanes have been calculated by the following equation (1).

$$GDF_i = \frac{M_i}{\sum_{j=1} M_j} \cdot N = \frac{E \cdot Z_i \cdot Z_l}{(\sum_{j=1} E \cdot Z_j \cdot Z_l)} = \frac{\frac{Z_i}{Z_l} \cdot \varepsilon_i}{(\sum_{j=1} \frac{Z_j}{Z_l}) \cdot \varepsilon_j} \cdot N = \frac{\varepsilon_i \cdot \omega_i}{(\sum_{j=1} \varepsilon_j \cdot \varepsilon_l)} \cdot N \tag{1}$$

where, GDF_i : GDF of girder in the i th place
M_i : Bending moment of girder in the i th place
E : Modulus of Elasticity
Z_i : Section property of girder in the i th place
Z_l : Section property of standard girder
ε_i : Maximum bottom flange strain of girder in the i th place
ω_i : Ratio of section property between girder in the i th place and standard girder
N_i : Number of loaded wheels

If all girders are produced in the same cross-section, GDF is described by the following equation (2).

$$GDF_i = \frac{M_i}{\sum_{j=1} M_j} = \frac{\varepsilon_i}{\sum_{j=1} \varepsilon_j} \tag{2}$$

2.2 AASHTO standard specification

The basic shape of GDF presented in AASHTO Standard Specification[7] is composed of girder space(S) and distribution factor (D) as indicated in the following equation (3).

$$GDF = \frac{S}{D} \tag{3}$$

where, distribution factor for inner girder ;
$D = 5.5ft, S < 14ft$
distribution factor for outer girder ;
$D = 5.5ft, S < 6ft$
$D = 4 + 0.25S,\ 6ft < S < 14ft$

Considering the specification excessively designed in the past, AASHTO standard specification (1996) newly defined distribution factor (D) as indicated in the following equation (4).

$$GDF = \frac{S}{D} = \frac{S}{11} \tag{4}$$

Generally, for structural analysis of bridge, transverse slab is expressed as girder element and analysis is made, supposing the determination of effective width for longitudinal element, the assessment of suitable width for transverse girder element and the dispersion of wheel load on the slab to joint load. On the contrary, since the expression suggested in AASHTO standard specification (1992,1996) considers girder space(S) only to get GDF, it is impossible to consider span length of bridge and number of lanes. Thus, it is impossible to properly cope with the alteration of span length or number of lanes.

Unlike the conventional standard, AASHTO LRFD standard specification (1998) defines GDF for girder space, span length and longitudinal strong variables and GDF of girder moment for number of loaded wheel is expressions (5), (6). However, since this expression is also used for straight bridge, there is restriction in applying it to prestressed concrete girder bridge with curved slab.

2.2.1 Two of more design lanes loaded

- Interior girders

$$GDF_i = 0.075 + (\frac{S}{2900})^{0.8} \cdot (\frac{S}{L})^{0.2} \cdot (\frac{k_g}{L \cdot t_s^3})^{0.1} \tag{5}$$

where,
S : Spacing of girders or webs
L : Span of girder
K_g : Longitudinal stiffness parameter
t_s : Depth of concrete slab
d_e : Distance from exterior web of exterior girder and the interior edge of curb or traffic barrier

- Exterior girders

$$GDF_{ext} = e \cdot GDF_i \tag{6}$$

where,

$$e = 0.77 + \frac{d_e}{2800},\quad k_g = n(I + A \cdot e_g^2),\quad n = E_B / E_D$$

E_B : modulus of elasticity of girder material
E_D : modulus of elasticity of deck material
I : moment of inertia of girder
A : area of cross-section
e_g : distance between the centers of gravity of the basic girder and deck

2.3 Problems in suggesting and studying other GDF

Considering the parameters such as perpendicular direction, width of slab, etc. which were not considered in AASHTO standard specification, Bakht[5] suggested a method to get the design distribution factor. However, since this expression considers girder space only, excluding span length, it does not sufficiently expresses actual reaction. Utiziling finite element analysis, Tarhini[13] suggested new expression in which study result on parameter affecting girder distribution was expressed as the function of girder space and span length through regression analysis(Bishara, Heins). However, this expression is also incomplete in that the difference of GDF between inner and outer girder is not reflected. As such, the current studies also have common problems of insufficient consideration on proving procedure of models and variables. Moreover, it is problematic to wholly apply the existing GDFs while there is no specification for girder distribution of prestressed concrete girder bridge with curved slab.

3. Analysis of numerical value to assess GDF of prestressed concrete girder bridge with curved slab

To evaluate the wheel influence on prestressed concrete girder bridge with curved slab, this dissertation executed the modelling of finite element of bridges with curved slab and straight slab to compare the girder distribution. Presenting problems assumed by current modelling technique by utilizing analysis result and generalizing the maximum girder distribution values occurred for various variables, The authors suggest the brief GDF of prestressed concrete girder bridge with curved slab.

3.1 Analysis method of prestressed concrete girder bridge with curved slab

To analyze prestressed concrete girder bridge with curved slab, it is require to select elements which can rationally consider geometric shape and to properly constitute them.

Generally, the girder of prestressed concrete girder bridge constructed in urban area is composed of simple girder, but slab is consecutively constructed by joint in every 3 span. While prestressed concrete girder bridge was mostly constructed by span of 20 ~ 30m, currently the span length reaches 40m sometimes thanks to the introduction of new construction method.

When designing prestressed concrete girder bridge with curved slab in domestic site, it is customary to analyze, supposing the respective Frame element centered on girder as described in Fig. 1(a). However, since the shape of constructed bridge is not approximate, when wheel load passes curved slab section, the influence of load on the girder is not properly evaluated. Thus, to accurately evaluate the load, finite element analysis is performed by dividing slab in curved line and girder in straight line as described in Fig. 1(b)[8]

To calculate GDF, prestressed concrete girder bridge with 73 curved slabs was constituted as analysis model for finite element analysis and when it comes to the wheel load, DB-24 standard truck load was loaded at 2-3 lanes in accordance with the standard specification of highway bridge.[3]

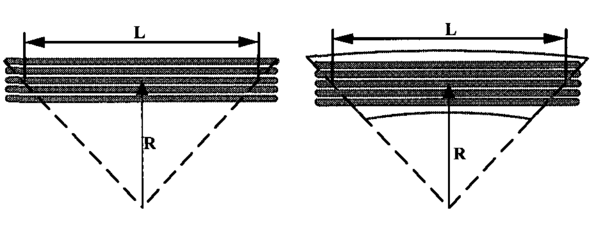
3.2 Evaluating the appropriateness of finite element analysis model

Comparing the on-the-spot test result and finite element analysis result of Ahyun Elevated Road, a prestressed concrete girder bridge with curved slab section constructed in urban area, this dissertation verified model element by which the actual reaction of bridge can be properly reproduced.(Ahyun Elevated Road, Report of precise safety check[15])

The section specification of Ahyun Elevated Road is as follows and the value of section property of bridge cross-section is indicated in Table 1.

- Bridge type: simple prestressed concrete girder bridge
- Number of lanes: 4 lanes
- Span length of slab curved section : 23.3 m ~ 26.7 m
- Grade of bridge: 2nd grade
- Curvature radius of slab: 150 m
- Design load: DB-18
- Bridge width : 15 m

Fig. 2 shows the cross-section of Ahyun Elevated Road, load position and LVDT position, the total weight of test wheel used in the load test is 266.54 kN. Grillage analysis in two dimensions using Frame elements only and slab are used for Shell elements.



(a) Model A (b) Model B

Fig. 1 Analysis model

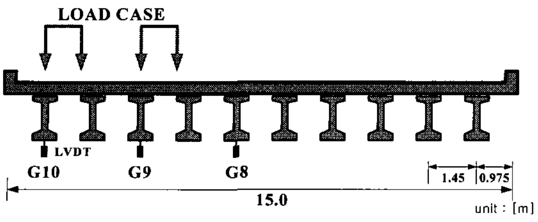


Fig. 2 Test section of Ahyun Elevated Road

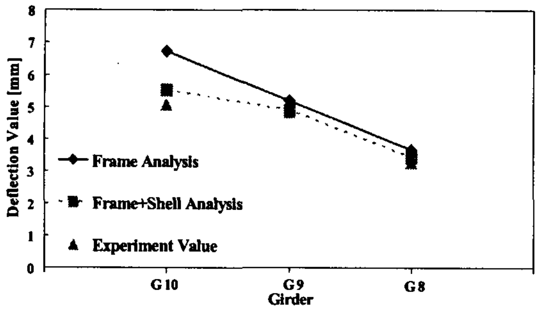


Fig. 3 Comparison of FEM analysis result and field test result

For girder, finite element analysis result in three dimensions constituted by Frame elements is mutually compared and Fig. 3 compares the respective finite element analysis result and on-the-spot test result.

As described in Fig. 3, analysis of three dimensions in which slab is modelled as second shell element of 4 joints and girder, as Frame element can express the actual reaction more exactly than grillage analysis of two dimensions in which only generally-used frame element is used. In Table 2, test value and deflection value for each girder of analysis are arranged.

In the case of grillage analysis of two dimensions, deflection value for each girder linearly changes as described in Fig. 3, but in the case of on-the-spot test value or analysis of three dimensions, the deflection by curved shape is well expressed at girder 10.

Thus, this research selected model of three dimensions that can exactly reproduce the reaction of prestressed concrete girder bridge with curved slab to execute analysis(Shahawy, McElwain).

3.3 Comparison of parameter for calculation of GDF

For calculation of GDF to briefly analyze prestressed concrete girder bridge with curved slab, the influence of parameter is evaluated as follows.[1] The cross section of girder with span of 30 m standardized for road construction was applied equally. The chosen parameters were composed of span length(L), curvature radius(R), girder space(SG), transverse girder space(SC), number of lanes(N), etc. as indicated in Table 3. For values of section property of girder, those suggested in Design Manual for Road Bridge[3] or Design Manual for Highway Bridge[2] were applied and analyzed. The relation between parameters to calculate GDF can be summarized as follows.

3.3.1 The influence of curvature

In the analysis model of prestressed concrete girder bridge with curved slab, the bridge was analyzed on the basis of curvature radius that is within the range in which shell elements forming slab by curvature radius does not interfere with frame elements forming straight girder.

The analysis result of curvature effect is indicated in Figs 4-5. As indicated in Figs. 4-5, the maximum girder distribution ratio of wheel load increases as curvature(1/R) increases. In the section where curvature is between 0.002 and 0.004, the value of girder distribution is less than that of AASHTO.

Table 2 Comparison of deflection between FEM analysis result and field test

Measuring position		Deflection(mm)
Girder 10 (1/2 L)	Frame analysis(2D)	6.72
	Frame+shell analysis(3D)	5.53
	Experiment data	5.07
Girder 9 (1/2 L)	Frame analysis(2D)	5.18
	Frame+shell analysis(3D)	4.89
	Experiment data	4.85
Girder 8 (1/2 L)	Frame analysis(2D)	3.66
	Frame+shell analysis(3D)	3.04
	Experiment data	3.26

Table 1 Section properties of Ahyun Elevated Road

Section-properties		Area(cm^2)	Inertia moment $I(cm^4)$	Slab	Prestressed concrete girder		e_p [2] (cm)
				y_c [1](cm)	y_t [1] (cm)	y_b [1] (cm)	
Girder center	Area of net(A_c)	4113	7047155	-	68.31	56.69	41.54
	Area of converted(A_n)	4394	7328416	-	69.92	55.08	39.94
	Area of composite section(A_{nc})	7094	18099914	59.50	39.50	85.50	70.35

Table 3 Parameter used to calculate GDF of prestressed concrete girder bridge with curved slab

Parameter	Quantity	Values
Span length(L)	2	29.1, 39.1 m
Curvature radius(R)	5	500, 400, 300, 200, 100 m
Girder space(SG)	5	2, 2.3, 2.5, 2.76, 3.3 m
Cross beam interval(SC)	4	4.85, 4.8875, 6.517, 7.275 m
Width of bridge(W)	2	12.145, 15.745 m
Number of lanes(N)	2	2, 3 Lane
Total	73	
Fixed values	Designed wheel : DB-24 Slab f_{ck} =26.48 *MPa* Thickness = 0.25 m Girder f_{ck} =39.23 *MPa* SWPC7B 12.7 mm 7 lines	

Especially, in the case of Fig. 5, if curvature gets larger than 0.005, girder distribution ratio becomes larger than AASHTO LRFD.[5] This means that girder distribution may vary conspicuously, depending on whether curvature is considered or not. Thus, it suggests that the existing GDF may be overestimated or underestimated, depending on the curvature. However, it is confirmed that the influence on the curvature of slab may be increased as analysis value of finite element analysis gets larger than girder distribution ratio of AASHTO LRFD[5] including safety ratio. This fact could be the most dangerous matter.

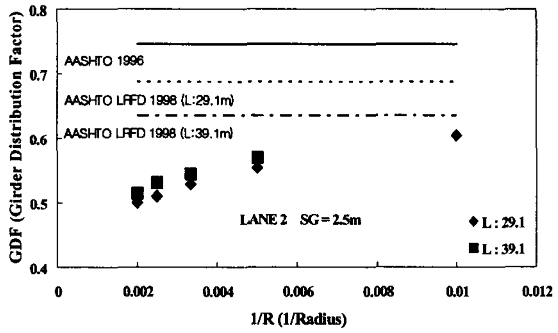


Fig. 4 Relation of GDF and 1/R at Lane 2, SG=2.5 m

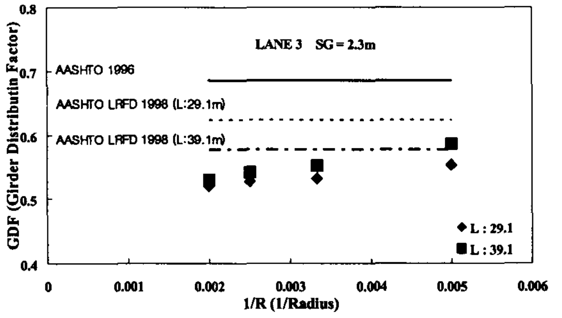


Fig. 5 Relation of GDF and 1/R at Lane 3, SG=2.3 m

3.3.2 The influence of span length (L)

Generally, the girder distribution ratio increases with the increment of span length of bridge. As indicated Figs. 6-7, the value of girder distribution does not increase considerably when the length of bridge increases from 29.1 m to 39.1 m, but it is subject to the general tendency of girder distribution.

3.3.3 The influence of number of lanes (N)

As indicated Figs. 8-9, the ratio of girder distribution increases with the increment of number of lanes, but it is confirmed that the number of lanes does not affect the ratio of girder distribution considerably.

3.3.4 The influence of girder space (SG)

As the main variable adopted for calculating GDF at AASHTO standard specification, girder space indicated the relation between SG subject to the variation of curvature radius and GDF in Figs. 10-11. As indicated in Figs. 10-11, the ratio of girder distribution is affected more in shorter curvature radius and under same conditions, if SG increases, it also increases as expected. Moreover, in the case of Lane 3, L=39.1 m, as the ratio of girder distribution at R=200 described in Fig. 11 turned out to be larger than ratio of distribution of AASHTO LRFD standard specification ,[5] it is confirmed that the difference of ratio of girder distribution is magnified owing to the curvature of slab.

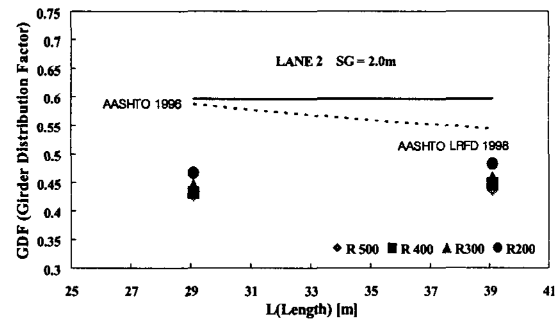


Fig. 6 Relation of GDF and L at Lane 2, SG=2.0 m

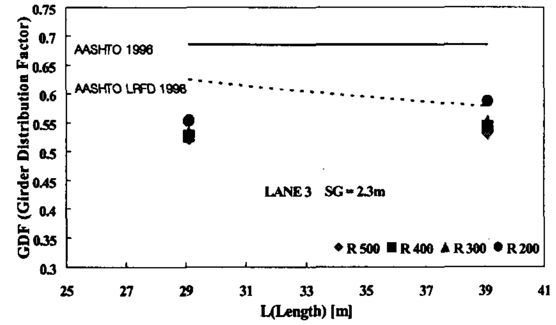


Fig. 7 Relation of GDF and L at Lane 3, SG=2.3 m

3.3.5 The influence of cross beam (SC)

The influence made on the variation of ratio of girder distribution by the interval of cross beam is indicated in Figs. 12-13. As shown in Figs. 12-13, the interval of cross beam of bridge is not a critical variable in the girder distribution.

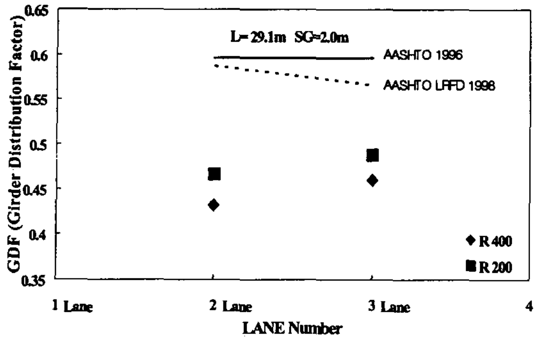


Fig. 8 Ratio of distribution for number of lanes at L=29.1

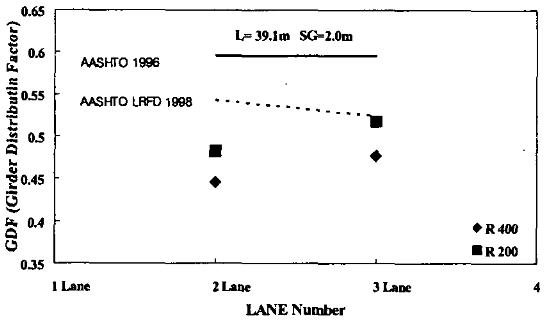


Fig. 9 Ratio of distribution for number of lanes at L=39.1

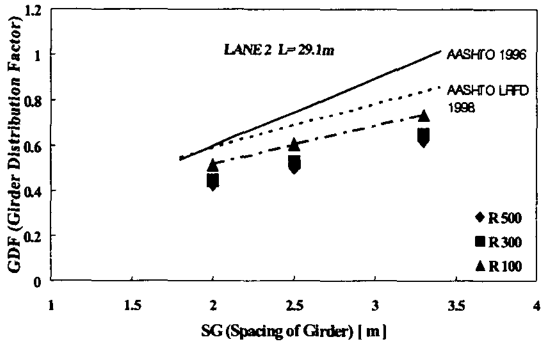


Fig. 10 Influence of girder space at Lane 2, L=29.1

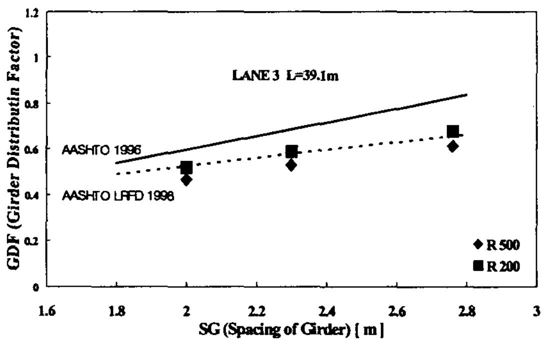


Fig. 11 Influence of girder space at Lane 3, L=39.1

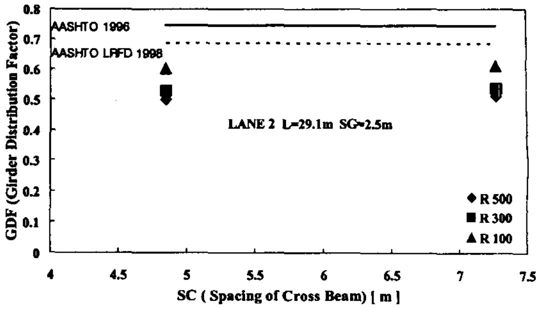


Fig. 12 Influence of the interval of cross beam at Lane 2, L=29.1, SG=2.5 m

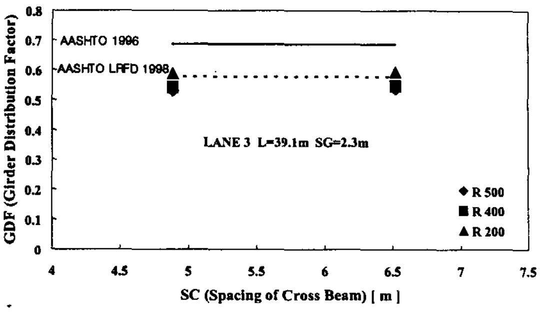


Fig. 13 Influence of the interval of cross beam at Lane 3, L=39.1, SG=2.3 m

4. Calculation of GDF of prestressed concrete girder bridge with curved slab

In the case of prestressed concrete girder bridge with curved slab, it is confirmed that value of girder distribution increases with the increment of span length, ratio of curvature radius (L/R) and girder space(SG), depending on the number of lanes. Through regression analysis of influence of these parameters, this dissertation suggested GDF which is indicated in the following equation (7) and (8).

- For 2 Lane,

$$GDF_{2Lane} = 0.1871 \cdot SG\left\{0.1272 \cdot Ln\left(\frac{L}{R}\right) + 1\right\} + 0.2157 \qquad (7)$$

- For 3 Lane,

$$GDF_{3Lane} = a_1 \cdot GDF_{2Lane} \qquad (8)$$

where, $a_1 = 1.1$

In Table 4 and 5 are presented GDF for each parameter analyzed from the finite element analysis result and GDF derived from expression suggested by expression (7) and (8) and in Table 4 is compared GDF of two loaded lanes.

Since the existing AASHTO LRFD standard specification[5] varies in compliance with the girder space and span length, it seems that applying girder distribution to bridge with curved slab has some limitation

Table 4 Comparison of FEM analysis and suggested expression at 2 lanes

Number of Lane (1)	SG [m] (2)	L[m] (3)	SC[m] (4)	R[m] (5)	FEM GDF(6)	Proposed GDF (7)	AASHTO LRFD['98](8)	RE[%] (9)
2	2	29.1	4.85	500	0.426	0.455	0.585	6.70
				400	0.432	0.465		7.68
				300	0.444	0.479		7.85
				200	0.466	0.498		6.90
				100	0.514	0.631		3.34
		39.1	4.8875	500	0.434	0.469	0.542	7.97
				400	0.446	0.479		7.45
				300	0.458	0.496		7.62
				200	0.482	0.512		6.27
	2.5	29.1	4.85	500	0.500	0.514	0.684	2.85
				400	0.510	0.528		3.44
				300	0.528	0.545		3.15
				200	0.554	0.569		2.66
				100	0.604	0.610		0.99
		39.1	4.8875	500	0.514	0.532	0.633	3.47
				400	0.530	0.545		2.85
				300	0.544	0.562		3.35
				200	0.570	0.586		2.87
	3.3	29.1	4.85	500	0.618	0.610	0.836	-1.33
				400	0.628	0.627		-0.11
				300	0.646	0.650		0.60
				200	0.674	0.682		1.15
				100	0.734	0.736		0.30
		39.1	4.8875	500	0.632	0.633	0.770	0.15
				400	0.648	0.651		0.39
				300	0.666	0.673		1.07
				200	0.694	0.705		1.58

Table 5 Comparison of FEM analysis and suggested expression at 3 lanes

Number of Lane (1)	SG [m] (2)	L [m] (3)	SC[m] (4)	R [m] (5)	FEM GDF (6)	Proposed GDF (7)	AASHTO LRFD['98](8)	RE[%] (9)
3	2	29.1	4.85	500	0.520	0.478	0.575	4.69
				400	0.527	0.490		6.54
				300	0.532	0.505		7.94
				200	0.553	0.526		7.87
		39.1	4.8875	500	0.530	0.494	0.532	5.98
				400	0.542	0.506		5.99
				300	0.552	0.521		7.13
				200	0.587	0.542		4.61
	2.3	29.1	4.85	500	0.457	0.518	0.547	-0.42
				400	0.460	0.531		0.81
				300	0.468	0.549		3.12
				200	0.488	0.573		3.62
		39.1	4.8875	500	0.466	0.536	0.524	1.06
				400	0.477	0.549		1.30
				300	0.486	0.566		2.60
				200	0.518	0.591		0.64
	2.76	29.1	4.85	500	0.598	0.578	0.710	-3.30
				400	0.607	0.594		-2.08
				300	0.614	0.615		0.19
				200	0.638	0.644		1.01
		39.1	4.8875	500	0.612	0.600	0.656	-2.03
				400	0.625	0.616		-1.48
				300	0.638	0.637		-0.23
				200	0.676	0.666		-1.51

On the contrary, the GDF suggested in this research is expected to reflect the shape of bridge by dividing and applying the value of girder distribution in accordance with the curvature radius. As described in Table 4, the value of wheel load distribution increases with the increment of curvature, producing difference from the value of girder distribution which does not reflect the curvature of AASHTO LRFD standard specification. Applying the suggested GDF and comparing it with the distribution value of AASHTO LRFD standard specification[5)], we find that excessive design is very prevalent, showing the inadequacy of the existing GDF. It seems that calculation of girder distribution through on-the-spot test of prestressed concrete girder bridge with curved slab should be made in the future for verifying suggested GDF by finite element analysis. The difference between finite element analysis result and suggested expression is compared by the relative error(RE) of expression(9). If relative error is positive(+), suggested expression is larger than finite element analysis result and if negative(-), smaller. Fig. 14 shows the comparison between calculated value by this suggested expression and analysis value by finite element analysis. For the ratio of girder distribution, calculated value and analysis value almost coincide with $GDF_{Proposed}/GDF_{FEM}=1$, showing good relativity. Here, left upper part indicates safe side of suggested expression against the distribution expression and right lower part, unsafe side

$$RE = \frac{GDF_{proposed} - GDF_{FEM}}{GDF_{FEM}} \cdot 100(\%) \qquad (9)$$

5. Conclusion

This dissertation executed modelling for each element to evaluate the influence of wheel load of prestressed concrete girder bridge composed of curved slab section and straight girder.

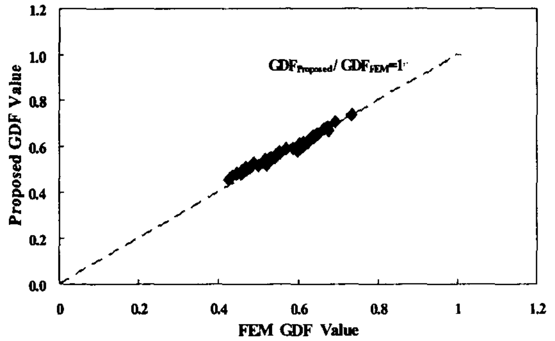


Fig. 14 Ratio of suggested expression and analysis value

In addition, parameter analysis was executed for varying location of bridge specification to suggest GDF of designed wheel.

1) In analyzing prestressed concrete girder bridge with curved slab, it is better to divide and analyze slab section by shell element and girder by frame element than to analyze total cross-section of bridge in various frame element (grillage analysis) in order to get values approximate to those measured at field.
2) Analyzing finite element of prestressed concrete girder bridge with curved slab by various selected parameters. The GDF of prestressed concrete girder bridge with curved slab is suggested. The GDF of prestressed concrete girder bridge with curved slab was indicated by function of natural log in accordance with span length and curvature radius. It was also confirmed that girder space is the main variable of girder distribution. However, the interval of cross beam did not largely affect girder distribution.
3) While the existing specification (AASHTO) is uniform GDF that does not reflect curvature, the suggested expression can calculate the rational value of girder distribution of prestressed concrete girder bridge with curved slab, because it is able to reflect the curvature radius of slab.
4) Wheel GDF of prestressed concrete girder bridge with curved slab is suggested utilizing finite element analysis. It is required to execute on-the-spot test of prestressed concrete girder bridge with curved slab several times so as to verify the suggested expression. To this purpose, it would be necessary to standardize influential coefficient for each elements and accumulate materials for diverse elements.

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