QUANTIFICATION OF INTERMEDIATE DIAPHRAGM EFFECTS OF PRESTRESSED CONCRETE GIRDER BRIDGES- APPLICATION TO LRFD DESIGN

C.S. Cai, **PhD, PE**, Louisiana State University, LA
Anand Chandolu, **MS**, Louisiana State University, LA and
Marcio Araujo, **Doctoral student**, Louisiana State University, LA

ABSTRACT

Construction of intermediate diaphragms (IDs) in prestressed concrete bridges is an extra cost financially and in schedule. Practice of intermediate diaphragms in prestressed concrete bridges is still controversial and the practice in each state is different. The Standard Specifications[1] recommend that intermediate diaphragms be used at the point of maximum positive moment for spans in excess of 12m (40 ft), but clear reasons for such requirements were not given. While it is stated in the LRFD Specifications[2] that intermediate diaphragms can improve live load distributions, this effect is not included in the calculation of load distribution factors. No significant work has been done in the past to quantify(with formulas) the influence of intermediate diaphragms on load distribution and the studies were limited to whether ID increases or decreases the load distribution factor (LDF). This study aims at quantifying the ID influence on load distribution. The approach adopted for deducing the correction factors has been presented. The correction factors when applied to LDF (load distribution factor) values from AASHTO codes yield an LDF value that accounts for the ID influence in load distribution. The way to apply these formulas in LRFD design code has been illustrated. The presented information will help engineers in examining the functions of IDs and in developing their policies of ID practice for prestressed concrete bridges.

Keywords: Intermediate diaphragm, Prestressed concrete bridge, Load distribution.

INTRODUCTION

As per the Standard Specifications [1] for Highway Bridges, "a diaphragm is a transverse stiffener, which is provided between girders in order to maintain section geometry." The diaphragms at the ends of bridges are called end diaphragms and the diaphragms away from the bridge ends are called intermediate diaphragms (referred as IDs or simply diaphragms hereafter).

The IDs are primarily used for the purpose of providing stability to girders during the process of construction. IDs are also considered to reduce the maximum load effects coming into the girder by distributing loads laterally. Current bridge design codes [1,2] specify the need of providing IDs for prestressed concrete girder bridges and also state that IDs influence the load distribution in bridges. But during the process of developing expressions for Load Distribution Factors (LDFs), which is the maximum amount of load coming on to the girder in terms of the number of wheel lines or design trucks, ID effects were not considered. That is to say that the current codes did not account for the influence of IDs in load distribution, though they state that IDs have a bearing on load distribution in bridges.

Most of the research done in the past on IDs in prestressed concrete girder bridges focused on whether IDs increase or decrease the LDF values, but no significant work was done to quantify(with formulas) the ID influence in load distribution. The objective of this study is to quantify the influence of IDs in load distribution with formulas. A parametric study was done by analyzing several bridge configurations using 3-D Finite Element models for both with and without IDs. From these results, expressions for correction factors were developed for LDFs for interior and exterior girders, as ID's influence on load distribution was observed to be different for these girders, with ID decreasing the LDF for interior girders and increasing this value for exterior girders. The values of correction factors when applied to the LDF values obtained by expressions used in LRFD codes gives an LDF value which accounts for the influence of IDs in load distribution. The procedure adopted in developing the expressions for these correction factors has been summarized in this paper. To ensure the accuracy of the formulas developed, the values of the correction factors obtained form these expressions are compared with the values obtained from 3-D finite element analysis for different bridge configurations. Few illustrations are presented to show how these expressions are applied to the LDF values obtained from AASHTO LRFD [2]. The expressions so developed could be used when designer intends to account for the influence of IDs in load distribution and could be useful in bridge rating as including the ID effect may increase or decrease the rating factor, which may make difference when the rating is near the "pass" or "fail" line.

LITERATURE REVIEW

A detailed review of research on the work done on the ID's influence in load distribution till date has been done. The summary of the review is presented here.

The first of the reports which raised the question on the need for IDs in PC bridges was the one by Lin and Van Horn [3]. From the field test results conducted on a bridge in Philadelphia, they reached the following conclusions: Diaphragms transmit the loads laterally; but when various lanes were loaded at the same time, the experimentally determined distribution factors were not appreciably affected and the deflections in the girders reduced slightly with the provision of IDs in bridges, thereby putting the advantage of IDs in load distribution into question.

Sithichaikasem and Gamble[4] carried out a parametric study for various bridge geometries for simply supported right bridges, to understand the influence of IDs in PC bridges. The following observations were made through this study:

- When the loading is close to exterior girders, the diaphragms increases the controlling moment hence prove to be detrimental while for other cases it may either be helpful or harmful.
- The influence of number of IDs in load distribution is insignificant and
- The IDs must be of correct flexural stiffness to be effective; otherwise any increase in diaphragm stiffness beyond a particular limit would increase the girder moments.

Similar results were obtained by Kostem and DeCastro[5] who performed a finite element analysis on two existing simple span non-skewed PC girder bridges. Other interesting observation they made was that only 20-30 % of the stiffness of RC diaphragms contributes to load distribution.

Wong and Gamble[6] also considered the same parameters as Sithichaikasem and Gamble[4], to determine the effect of diaphragms and continuity on load distribution in straight continuous bridges. The conclusions of this research were

- Changes in maximum moments are not sensitive to the diaphragm stiffness and the effects of diaphragms are more pronounced in simply supported bridges than in continuous bridges.
- The effects of continuity tend to cause a greater reduction for the maximum positive moment in the exterior girder than in interior girder.
- Bridges with a girder spacing to span length ratio less than 0.05, presence of diaphragms may do more harm than good.
- Except for temporary erection purposes diaphragms are not required in straight bridges.

Sengupta and Breen[7] conducted experimental tests on four test bridges, which were scaled down to 1/5.5 ratio with the variables being length, skew agle, and location of IDs for simply supported bridges under both static and dynamic loading in vertical and lateral direction. They observed a similar pattern of results as their earlier researchers.

From the research by Abendroth et al.[8] it was observed that the vertical load distribution is nearly independent of the type and location of the IDs. Griffin's [9] research on field bridges along a coal haul route indicated that IDs increase the load distribution (so reduce the load distribution factor) and reduce the girder deflection, but this is coming at a cost of increased construction and maintenance costs. Eamon and Nowark[10] studied the combined effects of secondary elements such as diaphragms, sidewalks, and barriers on load distribution in the elastic and inelastic domains. According to them diaphragms showed to reduce the maximum girder moment up to 13% with an average reduction of about 4%.

Cai et al.[11] analyzed six prestressed concrete bridges in Florida and the results from FEM were compared with field test results of these bridges. They observed that the finite element prediction without considering IDs or considering only partial ID stiffness contribution has better agreement with field test results than considering the full ID stiffness. Research by Khaloo and Mirzabozorg[12] indicated that effectiveness of IDs in skew bridges depends on the ID configurations.

From the current literature review it is evident that, though diaphragm effects were extensively studied, no significant effort has been made to quantify the influence of IDs in load distribution with formulas that can be used by practicing engineers to conveniently predict the ID effects. Therefore the current study is aimed at addressing the issue of quantifying the influence of IDs in load distribution with formulas, which could be instrumental in developing policies and practices pertaining to IDs in prestressed concrete bridges.

3-D FINITE ELEMENT MODEL

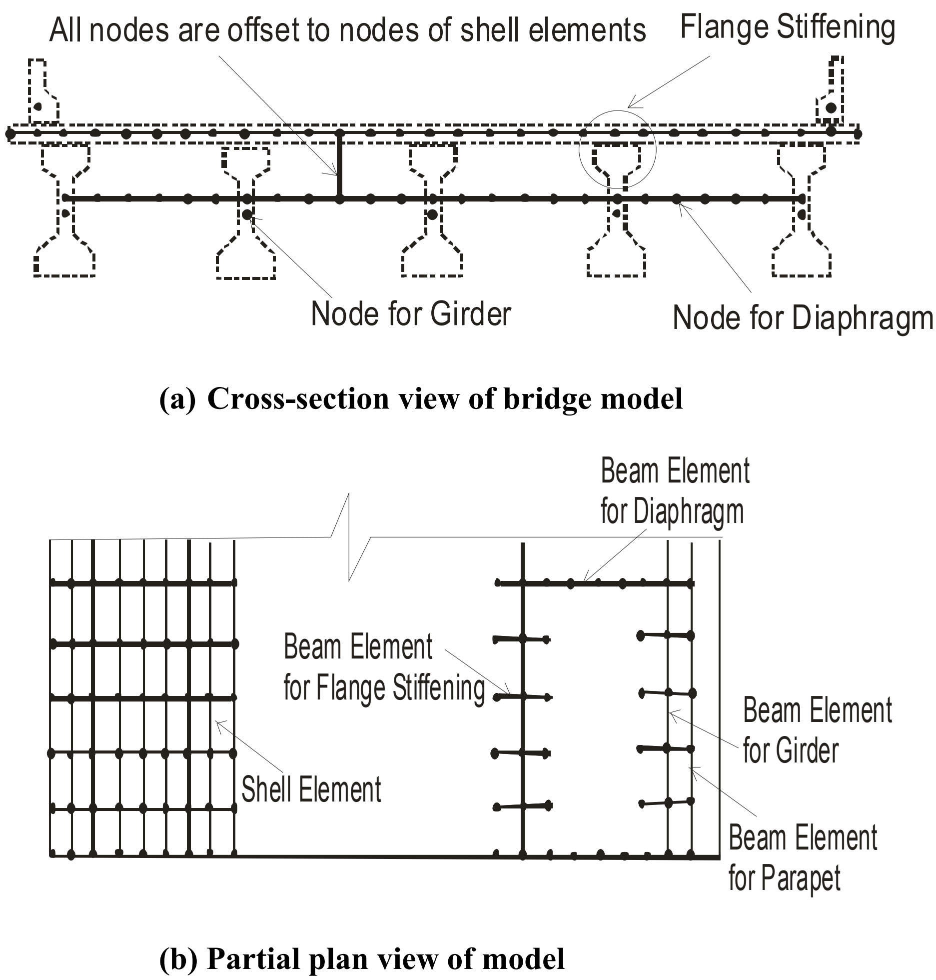

Fig. 1 Illustration of finite Element Model

A well calibrated simplified 3-D elastic finite element model built in GT STRUDL is used for analyzing all the bridges considered for the parametric study. The components of bridges were modeled using plate and line elements along the three dimensions of the bridge. The slab was modeled using four node quadrilateral plate bending elements along the plane of centroidal axis of the deck. Beams and diaphragms were modeled as line elements along their centroidal axis. These elements were formed by connecting nodes offset from the nodes used in modeling the deck, along their respective centroidal axis. Rigid links were used for connecting the beam and diaphragm elements to the slab. In case of continuous bridges, continuity was modeled along the span for deck elements only and girders were considered to be simply supported. An elevation and top view of this model is shown in Fig. 1. Before using this model for the parametric study the results from the simplified 3-D model were compared to that obtained from analysis of solid model built in ANSYS (all elements modeled using Solid45 element). For a few bridge configurations, the LDF values and strains were compared for loading conditions generating a maximum straining action for interior and exterior girders.

Fig. 2 shows the comparison between the micro-strain values for a bridge with a span length of 110 ft and a girder spacing of 9ft, both with and without IDs for a loading configuration generating a maximum straining action for an interior girder. It was observed that the difference in the values of strains and LDF values between the two models for the girder undergoing a maximum straining action (result of interest) is in order of 2% and 4% for loading configurations generating a maximum straining action for interior and exterior (not shown in the figure) girders, respectively. As the difference between the results obtained from the two models being small, the simplified model was used confidently for carrying out a parametric study.

In the present study, only truck loads were considered. Lane loads were not considered since truck loads and lane loads both have close load distribution factors. Therefore, though AASHTO LRFD code considers both lane and truck loads, its LDFs were based on finite element analysis of truck loads. Concrete diaphragms with a thickness of 8 in. were used in the present study. The diaphragm heights are different depending on the dimensions of the beam and obtained from the LaDOTD bridge design manual[13].

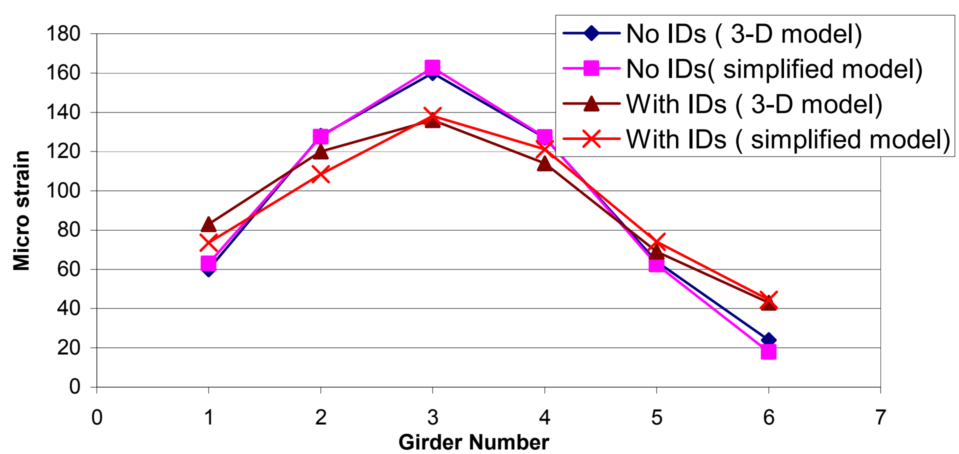

Fig. 2 Comparison between micro strain values obtained from the two models for loading generating maximum straining action for interior girder

PARAMETRIC STUDY

This study is limited to simply-supported and continuous, straight slab on girder bridges, both with and without skew. Only the standard AASHTO girders and Bulb-T beams were considered. A parametric study was done to understand the influence of IDs in load distribution for a wide range of bridge configurations. The parameters adopted in this study were, the type of girder, girder spacing, span length, ID type, skew angle, number of spans, and compressive strength of concrete in the girder. The values of the parameters are suitably chosen from a possible range of these variables so as to represent an entire range of bridges. As this project was meant for the state of Louisiana, the bridge configurations were chosen based on the specifications given in LaDOTD manual [13]. For all bridge configurations analysis was done both with and without IDs.

A preliminary parametric study was done to observe how the parameters affect the influence of IDs in load distribution by analyzing a few typical bridges. From this part of parametric study it was concluded that span length, skew angle, and girder type have significant effects on the *effect of ID on LDF* while continuity, girder spacing and compressive strength of concrete show no significant effects. Therefore span length, skew angle for bridges with different girder types were considered for a detailed parametric study. Along with these parameters girder spacing was considered for the detailed parametric study keeping in view the fact that the influence of girder spacing in LDF is significant. It needs to be noted that while girder spacing has significant effects on LDF, its effects on the *effect of ID on LDF* is insignificant.

All bridges considered were of two lanes with 50ft width, with lanes, shoulders and cantilevers of 12, 10, and 3ft, respectively. Skew angles of 0^o, 30^o and 50^o, and two girder spacings of 5 and 9ft were considered. Span lengths in the parametric study were varied from 50 to 130ft. Span lengths for a particular girder type were chosen based on the recommendations given by LaDOTD Manual[13].

Number of IDs was provided based on LaDOTD Manual[13] recommendations

- For $L \leq 15$ m, no IDs required.
- For 15 m $< L \leq 30$ m, Single ID.
- For $L > 30$ m, two IDs provided.

The diaphragms were considered to be perpendicular to the girder lines for right bridges, while in case of skew bridges IDs were considered to be perpendicular to the girder line but staggered to keep an equal distance from the location of support for each ID. IDs were considered to connect the girders in web region of the girder and the end diaphragms extend from the bottom of the slab to the bottom flange of the girder. All IDs have rectangular concrete section with 8 inches thickness.

With all these parameters and configurations of bridges, analysis was done with two lanes of bridge loaded (HS-20 trucks) to generate maximum straining action at the mid-span for interior and exterior girders. In order to determine the LDF values for interior girders, the trucks are to be moved laterally to examine which interior girder is most critical. But as in this research the interest being on how ID influences the load distribution, the loading configuration generating the maximum straining action on any interior girder would give approximately the same change in LDF caused due to diaphragms. In order to reduce the number of cases to be analyzed, the analysis was done for loading configurations that generate a maximum straining action in the innermost girder for all bridges.

LDF was calculated by dividing the strain in a particular girder to the summation of strains in all the girders at the same section obtained from finite element model and multiplying this factor with the number of wheel lines [14]. The change in LDF caused due to IDs (referred as R_d) in percentage is determined for all bridge configurations as:

$$R_d = ((LDF_{\text{value without ID}} - LDF_{\text{value with ID}}) / LDF_{\text{value without ID}}) * 100 \quad \textbf{(1)}$$

DEVELOPMENT OF FORMULAS FOR ID EFFECT ON LDF

From the results obtained from the parametric study, initial attempts made to develop an overall relationship between all the concerned parameters and the *effect of ID on LDF* was not successful. Therefore the expressions for R_d were developed systematically in parts. From the parametric study the following observations were made: (1) presence of IDs decreases LDF for interior girders but increases the LDF for exterior girders to different extents for different bridge configurations; (2) R_d is significantly different for skewed and non skewed bridges; (3) R_d is significantly dependent on the location of IDs; as the distance between the ID and the section at which results are considered increases, *effect of ID on LDF* decreases. Keeping these observations in view, expressions for R_d were developed differently for interior and exterior girders, and for bridges with single and two IDs. Initially R_d is developed for right bridges with different girder types in terms of span length and the expressions for R_d for different girder types are related to each other in terms of a variable C, as will be discussed later. Single ID was considered for bridges with Type II, III and IV girders as span lengths for these bridges are usually less than 30 m. Two IDs were considered for bridges with Type IV and BT girders as these girders are provided when the span lengths are greater than 30 m.

Fig. 3 shows the relation between the span length and R_d due to IDs for right bridges with different girder types for interior girders with a single ID. It could be observed that the relationships between these values are linear for each girder type and are nearly parallel to each other. These linear relations will serve as the basis in developing basic formulas on which correction factors will be applied and will be discussed later. Similarly relation was developed for exterior girders of bridges and for bridges with two IDs, though the trends and equations developed are different.

Influence of skew angles on *ID effect on LDF* was considered by multiplying a skew correction factor (S_K) to the already developed R_d expression for right bridges. S_K is defined as the ratio of R_d obtained for skew bridges and the R_d value obtained for corresponding right bridges. These values were observed to be close for bridges with single ID or two IDs for any particular skew angle. Based on the values of these factors a conservative skew correction factor is chosen for 30^o and 50^o skew angles. Skew correction factor for 0^o skew angle is equal to 1. A linear relation between any intermediate skew angles was observed to fit well for different bridge configurations for both interior and exterior girders.

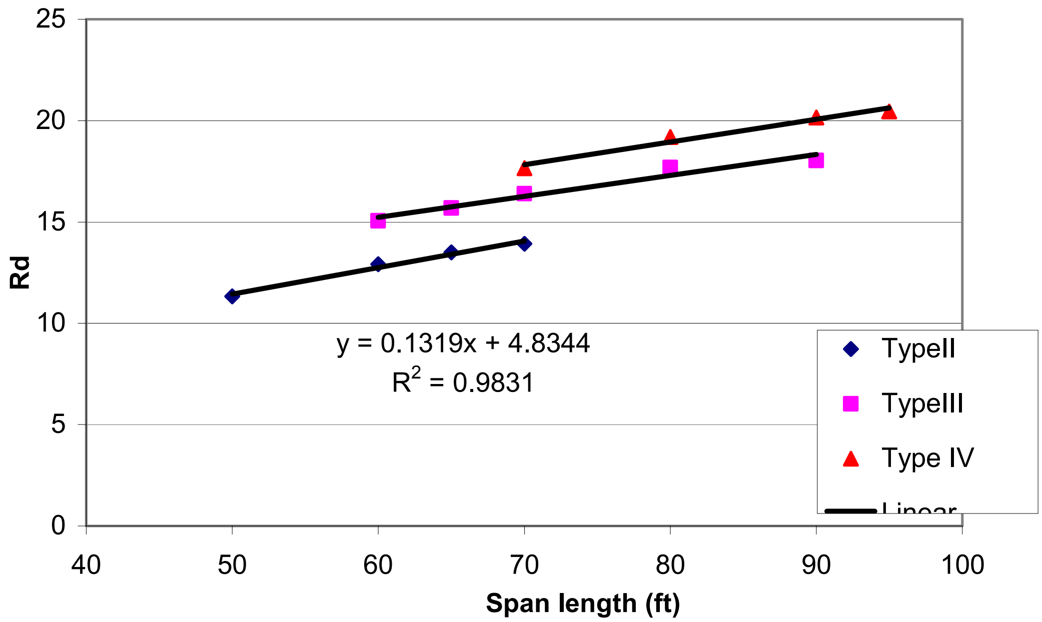

Fig. 3 Relation between span length and reduction in LDF due to ID for different girder types

Table 1 presents the S_K values for interior girders in bridges with a single ID. From these values in Table 1, the S_K values of 0.55 and 0.4 were adopted for 30° and 50° skew angles, respectively and are presented graphically in Fig 4. From Table 2 it could be observed that the R_d values obtained by applying skew correction factor (S_k) to R_d values obtained for right bridge is close to the actual R_d values for skew bridges obtained directly from FEM. Similar approach was adopted for developing expressions for skew correction factor for other cases as well.

Table 1 S_K for interior girders with single ID

Span Length (ft)	Skew = 30°		Skew=50°	
	Spacing (ft)			
	5	9	5	9
50	0.681	0.637	0.442	0.460
65	0.563	0.585	0.504	0.430
70	0.561	0.598	0.506	0.427
90	0.561	0.594	0.456	0.417

Table2. Checking accuracy of S_K for interior girders with single ID

Skew angle (degrees)	Skew correction factor (Fig. 4)	R_d values for skewed bridge (%)		
		FEM Analysis (1)	Based on Formulas (2)	(1) - (2)
15	0.775	13.6	13.8	-0.2
30	0.55	10.7	9.8	0.9
40	0.475	8.6	8.5	0.2
50	0.4	7.9	7.1	0.8
60	0.325	6.2	5.8	0.4

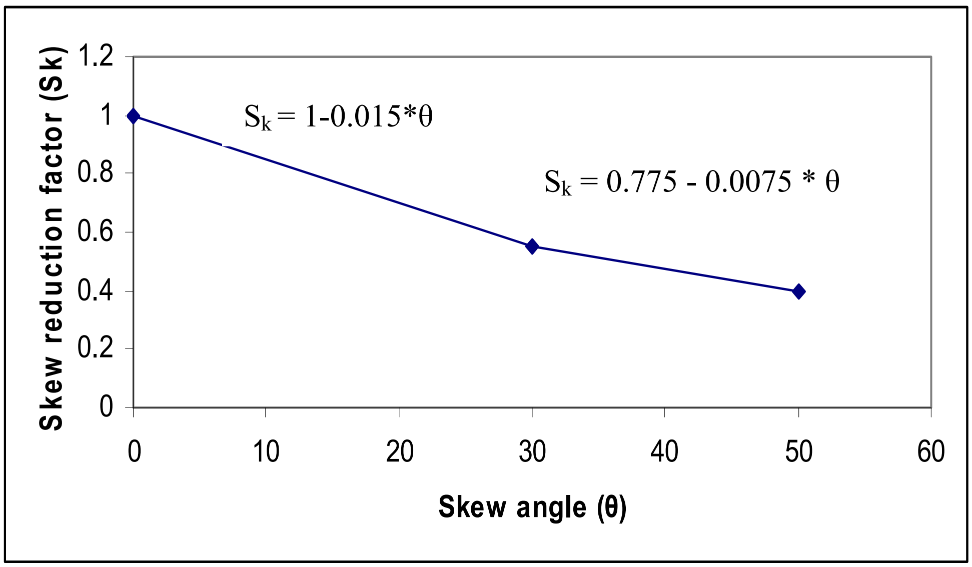

Fig. 4 Skew correction factor for interior girder of bridge with single ID

STIFFNESS REDUCTION FACTOR FOR INTERIOR GIRDER

As the connection between IDs and girders being essentially a cold joint with usually one or two reinforcement bars connecting these elements, the rigidity at the connection is variable and is related to the load levels [14]. At low loads the connection is close to full moment connection. As loads increase up to the ultimate stage, the cold joint may crack and open, leaving only the steel reinforcement to be effective in the tension region of the ID-girder interface. Therefore only a portion of the ID section stiffness may contribute to the load distribution. Determining the actual stiffness contributed by IDs to load distribution is beyond the scope of this study as it would demand a nonlinear finite element analysis or experimental studies to know the extent of cracking at the ID girder interface.

In order to take into account the effect of cracking at ID-girder interface, a stiffness reduction factor (S_t) was introduced for interior girders, which is the ratio of R_d value obtained by considering partial stiffness of ID to R_d value obtained by considering absolute (full) ID stiffness. By considering different possible stiffness contribution of ID in load distribution for different bridge configurations, a relation was developed between the S_r and S_t, where S_r is the ratio of possible (partial) ID stiffness contributing in load distribution to the absolute (full) ID stiffness expressed in terms of percentage. If the possible ID stiffness contributing in load distribution is determined (which is currently under development), a corresponding S_t value could be calculated through which R_d value could be obtained finally. S_t is not included in the R_d expression for exterior girders as ID increases the LDF for exterior girder and taking absolute (full) stiffness of ID in load distribution leads to more conservative results for exterior girders.

The expression developed between S_r and S_t for bridges with two IDs for Type IV and BT girders is presented in Fig.5, and they are exponential curves. A similar approach was used in building a relationship between S_r and S_t for bridges with a single ID where a single expression between S_r and S_t was found to be adequate.

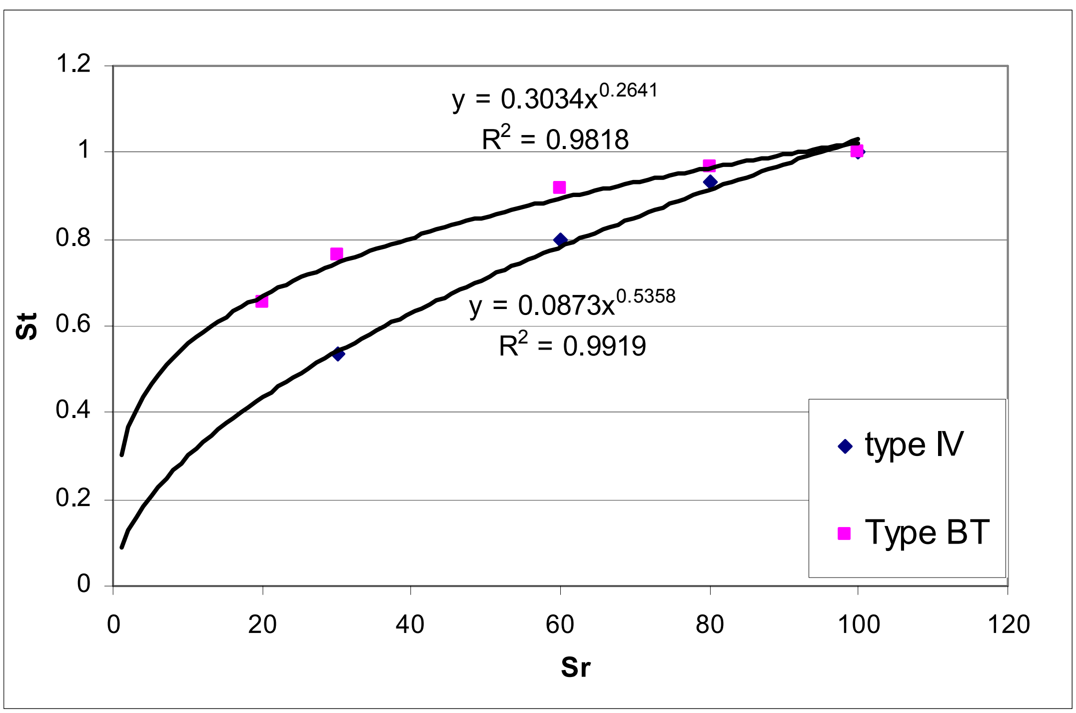

Fig. 5 Relation between ratio of possible stiffness and absolute ID stiffness to the stiffness correction factor ($y = S_t$ and $x = S_r$)

LOADING POSITION FACTOR FOR EXTERIOR GIRDER

In the parametric study the closest wheel line of loading system to the exterior girder was considered to be 12 in. This was because an 18 in. thick barrier was assumed (considered only in placing the loading system but not in design) along the edges and the wheel line must be at least 24 in. from the interior edge of the curb per AASHTO code[2], thereby making the total distance between the wheel line and the bridge edge equal to 42 inches. As the width of the cantilevering portion of the bridge is 30 in, the distance between the closest wheel line and the center of the exterior girder becomes 12 inches. In reality the width of the barrier and the cantilever portion of bridge could be different, which might affect the position of the loading system that generates the maximum straining action in the exterior girder. This change in location of loading system relative to the exterior girder influences the *ID effect on LDF* as could be seen from Fig. 6, which shows the relation between the lateral position of loading system with respect to the exterior girder and R_d for bridges with a span length of 90ft and for different girder spacing.

To account for the influence of the lateral position of loading system a new factor P_L was introduced for exterior girders. This correction factor is multiplied with the expression already developed for R_d, from the results obtained in the parametric study. Later it is checked whether the correction factor is applicable for bridges with other span lengths and girder spacing. It was observed that the difference between R_d value from the expression developed and the value obtained by FEM is about 2%, which being small indicates that the usage of this correction factor is accurate.

$$P_L = 0.45+0.55*d \quad (2)$$

Where d = distance between the lateral position of loading system to the exterior girder in ft.

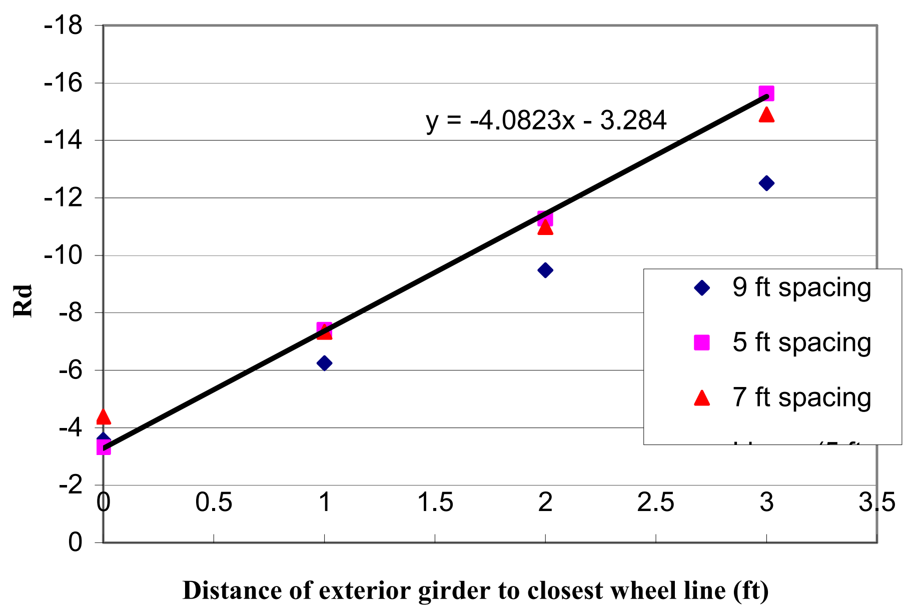

Fig. 6 Relation between lateral position of loading system and R_d for exterior girder

FINAL SET OF FORMULAS DEVELOPED

The approach discussed above is adopted to cover the whole range of bridge configurations and to include all possible major parameters affecting the *effect of ID on LDF*. The results of this study are summarized in Tables 3 to 5. The expressions for R_d developed are presented in Table 3 and the expressions for S_t, S_k and P_L are presented in Table 4. The values of C in expressions for R_d for different girder types are presented in Table 5.

Table 3. Expressions for R_d for different cases

No. of diaphragms	Interior(In) or exterior (Ex)	Equation for R_d
1	In	$[(0.132*L + 4.85) + C] *S_t *S_k$
2	In	$(-0.112*L +25.81) * C*S_t* S_k$
1	Ex	$(0.132* L -15.81 – C)* P_L* S_K$
2	Ex	$(-19.05 +0.147 * L – C)*P_L * S_K$

Table 4. Values of S_K, S_t and P_L for different bridge configurations

No. of dia.(D)	Interior girder		Exterior girder	
	S_K	S_t	S_K	P_L
1	$1-0.015*\theta$ $(\theta \le 30^o)$ $0.775 - 0.0075 * \theta$ $(\theta > 30^o)$	$0.0264*X^{0.8062}$	$1-0.01* \theta$ $(\theta \le 30^o)$ 0.7 $(\theta > 30^o)$	$0.45+0.55* d$ $(0 \le d \le 3ft)$
2	$1-0.0167*\theta$ $(\theta \le 30^o)$ $0.725 – 0.0075 * \theta$ $(\theta > 30^o)$	$0.0873*X^{0.5358}$ (Type IV) $0.3024*X^{0.2641}$ (Type BT)	$1-0.013* \theta$ $(\theta \le 30^o)$ 0.6 $(\theta > 30^o)$	$0.45+0.55* d$ $(0 \le d \le 3ft)$

Table 5. Values of C in expression for R_d

Girder Type	Interior		Exterior	
	No. of diaphragms		No. of diaphragms	
	1	2	1	2
II	0	-----	0	----
III	2	-----	3	----
IV	3.5	----- 1	5	0
BT	-----	1.98	-----	4

In the Tables 3 to5
L= Length of the girder in ft
C = constant
R_d = % reduction in load distribution due to diaphragm
P_L = Correction factor for taking into account position of lateral loading system
d = Distance between center of exterior girder to wheel line closest to edge in ft ($0 \le d \le 3$ft)
S_K = Skew reduction factor
S_t = Stiffness reduction factor
θ = Angle of skew
X = S_r = (Possible diaphragm stiffness contributing to load distribution / absolute diaphragm stiffness)*100

Finally the LDF for the bridge, which takes into account the influence of diaphragms in load distribution, could be given by the following expression:

$$(LDF)_{WD} = (1 - R_d / 100)*(LDF)_{ND} \quad \textbf{(3)}$$

Where
$(LDF)_{ND}$ = Load distribution factor from AASHTO LRFD[2] where no ID effects on LDF are considered.
$(LDF)_{WD}$ = Modified LDF by including diaphragm effects on LDF

The accuracy of the formulas developed for interior and exterior girders for different skew angles is checked by comparing the maximum, minimum, and absolute average difference in the R_d values obtained from formulas to the values of R_d obtained from FEM (see Table 6). Though in some cases, a significant difference (6%) exists between the maximum and minimum values, the absolute average difference is small thereby justifying the correctness of the formulas developed. Several other bridge configurations were analyzed which were not used in developing the formulas and for these bridge configurations the expressions developed were observed to give accurate results as well.

Table 6. Maximum, minimum, and absolute average difference between R_d values obtained from FEM and the values obtained from formulas

Interior or Exterior girder	Skew Angle (degrees)	Difference in R_d values		
		Minimum	Maximum	Absolute average
Interior	0 30 50	-1 -0.2 -0.7	1 3.7 6	0.5 1.2 1.8
Exterior	0 30 50	-2.3 -0.2 -1.1	2.6 1.5 1.7	1.1 0.5 0.6

EXAMPLES OF R_d CALULATIONS

In this section examples are illustrated for determining the LDF by accounting the influence of IDs on LDFs through the expressions for R_d listed in Tables 3 to 5. Four bridge configurations were chosen for this illustration and these are listed in Table 7.

Table 7. Bridge configurations for which calculation of R_d is illustrated

Case	Girder Spacing (ft)	Span length (ft)	Girder Type	Interior(In) or Exterior (Ex)	Skew (Degrees)	% ID Stiffness	d (ft)
1	9	130	BT	In	30	30	----
2	5	70	III	In	0	45	----
3	9	65	II	Ex	30	-----	2
4	9	110	IV	Ex	50	-----	0

Case 1 (Interior Girder)

Bridge being of 130ft long would have two diaphragms. As this case is for the interior girder the expression for $R_d = (-0.112*L + 25.81) * C*S_k* S_t$ (From Table 3)
Since girder type being BT, C = 1.98 (From Table 5)
For interior girder with two diaphragms

$S_t = 0.3024*X^{0.2641} = 0.3024*(30)^{0.2641} = 0.742$ (From Table 4)

$S_k = 1-0.0167*\theta$ as $(\theta \leq 30^o)$ = $1- 0.0167*30 = 0.5$ (From Table 4)

Therefore,

$R_d = (-0.112*L +25.81) * C*S_k* S_t = (-0.112*130 +25.81) * 1.98*0.5*0.742 = 8.26$

$(LDF)_{ND} = 1.36$ (From AASHTO LRFD[2])

$(LDF)_{WD} = (1 - R_d / 100)*(LDF)_{ND} = (1- 8.26/100)*1.36 = 1.25$

Case 2 (Interior Girder)

Bridge being of 70ft long would have a single diaphragm. As this case deals with the interior girder the expression for $R_d = [(0.132*L + 4.85) + C] *S_t *S_k$ (From Table 3)
For Type III girder, C = 2 (From Table 5)
For interior girder with single diaphragm

$S_t = 0.0264*X^{0.8062} = 0.0264*(45)^{0.8062} = 0.568$ (From Table 4)

$S_k = 1-0.015*\theta = 1- 0.015*0 = 1$ (From Table 4)

Therefore,

$R_d = [(0.132*L + 4.85) + C] *S_t *S_k = [(0.132*70 +4.85) +2]*0.568*1 = 9.11$

$(LDF)_{ND} = 1.00$ (From AASHTO LRFD[2])

$(LDF)_{WD} = (1 - R_d / 100)*(LDF)_{ND} = (1- 9.11/100)* 1.00 = 0.91$

Case 3 (Exterior Girder)

Bridge being of 65ft long would have a single diaphragm. As this case deals with the exterior girder the expression for $R_d = (0.1319* L -15.81 -C)* P_L* S_K$ (From Table 3)
For girder being Type II, C = 0 (From Table 5)
For exterior girder with single diaphragm

$P_L = 0.45+0.55* X = 0.45 +0.55*2 =1.55$ (From Table 4)

$S_k = 1-0.01* \theta = 1-0.01* 30 = 0.7$ as $(\theta \leq 30^o)$ (From Table 4)

Therefore,

$R_d = (0.1319* L -15.81 –C)* P_L* S_K = (0.1319*65 -15.81 – 0)*1.55*0.7 = -7.85$

$(LDF)_{ND} = 1.21$ (From AASHTO LRFD[2])

$(LDF)_{WD} = (1 - R_d / 100)*(LDF)_{ND} = (1 + 7.85/100)*1.21 = 1.31$

Case 4 (Exterior Girder)

Bridge being of 110ft long would have two diaphragms. As this case deals with the exterior girder the expression for $R_D=(-19.05 +0.147 * L - C)*P_L * S_K$ (From Table 3)
For Type IV girder, C = 0 (From Table 5)
For an exterior girder with two diaphragms

$P_L=0.45+0.55* X = 0.45 +0.55*0 =0.45$ (From Table 4)

$S_k = 0.6$ as $(\theta > 30^o)$ (From Table 4)

Therefore,

$R_d = (-19.05 +0.147 * L - C)*P_L * S_K = (-19.05 +0.147*110 – 0)*0.45*0.6 = - 0.77$

$(LDF)_{ND} = 1.10$ (From AASHTO LRFD[2])

$(LDF)_{WD} = (1 - R_d / 100)*(LDF)_{ND} = (1+ 0.77/100)*1.25 = 1.11$

The above calculations have demonstrated how to calculate the diaphragm reduction factor R_d and how to apply it to the LDF specified in the design code. No effort was made in the present study in improving the accuracy of the existing code LDFs. The developed R_d is to include the effect of IDs on load distributions. These four examples showed that the ID effects on load distribution ranges from 1 to 10%. Since dead load may be the major load; the ID effect on load distribution can generally be ignored in new bridge designs. However, in some cases, 10% difference in live load distribution may affect the rating of existing bridges and thus affect the decision to post the bridge. Therefore, it may be worthwhile to include the ID effects in some cases.

CONCLUSIONS

While there have been many researches on the effect of diaphragms on load distributions in the last few decades, no significant work was done in the past to quantify the influence of IDs in load distributions by developing formulas. Through this work expressions have been developed to account for the influence of IDs in load distribution for prestressed concrete bridges. The expressions developed were found to be accurate by comparing the values obtained from the expressions to that obtained from 3-D finite element analysis for different bridge configurations. These correction factors when multiplied with the LDF values obtained with AASHTO LRFD code conveniently accounts for ID influence in load distributions. This provides a useful tool for practicing engineers who may choose to account for the ID effects in both the rating of existing bridges and/or design new bridges.

The writers would like to emphasize that the present study is not intended to provide another set of LDF for bridge designs or to complicate the present design procedure. The intension is to quantify the intermediate diaphragm effects on load distributions with convenient formulas for practicing engineers when they need them. In majority cases the practicing engineers can balance the benefits and costs in using IDs and choose not to consider the ID effects. However, in some cases it may be worthwhile to consider this effect for the rating of existing bridges since that may make a difference when deciding if a bridge should be posted.

ACKNOWLEDGMENTS

The authors are thankful to Louisiana DOTD and Louisiana Transportation Research Center (LTRC) for making this study possible through their financial support. Mr. Walid Alaywan is the Project Manager.

REFERENCES

[1] AASHTO (2002). “Standard specification for highway bridges.” Washington, D.C.

[2] AASHTO 2004). “LRFD bridge design specifications”. Washington, D.C.

[3] Lin, C. S. and VanHorn, D. A., (1968). “The effect of midspan diaphragms on load distribution in a prestressed concrete box-beams bridge.” *Fritz Engineering Laboratory Report* No. 315.6, Lehigh University Institute of Research.

[4] Sithichaikasem, S. and Gamble, W. L., (1972). “Effects of diaphragms in bridges with prestressed concrete I-section bridges.” Structural Research Series No. 383, Illinois Cooperative Highway Research Series No. 128, University of Illinois at Urbana-Champaign, Urbana, Ill.

[5] Kostem, C.N. and DeCatro, E.S. (1977), “Effects of Diaphragms on Lateral Load Distribution in Beam-Slab Bridges.” *Transportation Research Record no.645*, Transportation Research Board, Washington D.C., 6-9.

[6] Wong, A. Y. C. and Gamble, W. L., (1973). “Effects of diaphragms in continuous slab girder highway bridges.” Structural Research Series No. 391, Illinois Cooperative Highway Research Series No. 138, University of Illinois at Urbana-Champaign, Urbana, Ill.

[7] Sengupta, S. and Breen, J. E., (1973). “The effects of diaphragms in prestressed concrete girder and slab bridges.” Research Report 158-1F, Project 3-5-71-158, Center for Highway Research, University of Texas at Austin, Texas.

[8]Abendroth, R. E., Klaiber, F. W. and Shafer, M. W. (1995). "Diaphragm effectiveness in prestressed-concrete girder bridges." *J. Struct. Engrg.*, ASCE, 121(9), 1362-1369

[9] Griffin, J.J. (1997), "Influence of Diaphragms on Load Distribution in P/C I-girder Bridges." *PhD Dissertation*, University of Kentucky.

[10] Eamon, C. D. and Nowak, A. S. (2002). "Effects of Edge-Stiffening Elements and Diaphragms on Bridge Resistance and Load Distribution." *J. Bridge Engrg.*, ASCE., 7(5), 258-266.

[11] C.S.Cai, Mohsen Shahawy and Robert, J. Peterman. (2002). "Effect of diaphragms on load distribution of prestressed concrete bridges" *Transportation Research Report, J. of the Transportation Research Board,* National Research Council, Washington D.C., No. 1814, pp. 47-54.

[12] Khaloo. R. and Mirzabozorg. H.(2003), " Load Distribution Factors in Simply Supported Skew bridges". *Journal of Bridge Engineering.,* ASCE 8 (4) , 241-244.

[13] LA DOTD (2002) *"*Bridge Design Manual*," Louisiana Department of Transportation and Development,* Baton Rouge, LA 241-244.

[14] C.S.Cai, Mohsen Shahawy(2004). "Predicted and Measured Performance of Prestressed Concrete Bridges". *Journal of Bridge Engineering*, ASCE, Vol 9, No.1, pp. 4-13.