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16.Abstract

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The objectives of this research were (1) to assess the need of reinforced concrete (RC) IDs in PC girder bridges and to determine their effectiveness, and (2) to search for a possible alternative steel diaphragm configuration that could replace concrete diaphragms if necessary.

The research team has examined and reviewed state-of-the-art technology and current practices from many sources of information on IDs. Through a survey questionnaire and review of the Louisiana Department of Transportation and Development (LADOTD) Bridge Design Manual, the research team obtained relevant information regarding the ID practices in Louisiana. Through the LADOTD data base for all state bridges, and from direct interaction with district engineers, several of the bridges that are of interest for this study were selected for field inspection. From these field trips to various bridge locations, much information has been acquired from the bridges themselves, as well as from the district engineers. Systematic parametric studies for various bridge configurations, which are representative of an entire range of bridge geometries with different parameters, were analyzed through simplified and solid finite element models. This study was performed on right and skewed bridges, which are simply supported and continuous. A reduction factor that could be multiplied by the AASHTO load distribution factor to account for the influence of the diaphragm in load distribution was developed. A finite element analysis was carried out using 3-D solid models to assess the effectiveness of various diaphragms in protecting the girders against the lateral impact and to determine the design forces in the steel bracing members during construction of deck.

The results from the parametric studies indicated that several parameters such as skew, span length, spacing, stiffness of diaphragm and girder have different levels of influence on the effectiveness of diaphragms in live load distribution for bridges. Correction factors that could quantify the ID influence on load distribution were developed. Results from various studies indicated that a steel diaphragm section can possibly replace the RC diaphragms.

A prestressed concrete bridge was tested in the field. This bridge was selected by an inspection team comprised of personnel from FHWA, LADOTD, and the LSU research team and is located over Cypress Bayou on LA 408 East, in District 61. A comprehensive instrumentation and loading scheme is presented and illustrated in this report. The instrumentation consists of LVDTs – Linear Variable Differential Transformers (to measure the midspan deflection of each girder), accelerometers, strain gauges, and acoustic emission sensors. The measured results are presented, and comparisons are made between the finite element model and the field tests.

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Assessing the Needs for Intermediate Diaphragms in

Prestressed Concrete Bridges

(Summary of Report)

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IMPLEMENTATION STATEMENT

This research focuses on the LADOTD design guidelines/specifications; therefore the audience is state highway engineers and professional consulting engineers. Keeping this in mind, the research team sought a reasonable balance between simplicity and accuracy in developing practical formulas and design aids. To ensure a smooth transition to a new design practice, any concerns from the LADOTD designers must be addressed. With this in mind, early input was sought from users through telephone interviews, surveys, and personal contact. Particularly, LADOTD structural and bridge engineers have been contacted for their comments to facilitate the implementation process in the future.

The research results will be presented to the state's structural and bridge engineers who may take a leadership role in implementing the findings. The research results will also be presented at conferences and in journals. Dissemination of these results will help the implementation process, and feedback from practical engineers will help measure the progress of implementation. The future monitoring of the new practice, i.e., bridges without IDs or with new types of IDs (for example, steel diaphragms), will also help guide successful implementations.

Specifically, the following are recommended for implementation:

1. For the purpose of load distribution, IDs can be eliminated, and the bridge strength will still exceed that required by the AASHTO specifications. However, IDs should continue to be used for construction and impact protection if other measures are not provided.

2. Impact studies indicated that RC IDs provided the greatest protection to girders if the impact took place near the ID. If IDs are to be provided to protect against impact, they must be placed at locations of possible impact. The research shows that concrete IDs provide better protection against the collision of over-height trucks. Therefore, concrete IDs are recommended where collision protection is required.

3. For the purpose of construction stability, steel IDs can be used to replace the concrete IDs. Therefore, where collision protection is not required, such as in the case of bridges over bayous, steel IDs can be used in place of the current concrete IDs.

4. When collision protection is not required and the contractor provides temporary supports during the construction, then the IDs can be eliminated. If the IDs are eliminated completely, the strain action for the interior girders will increase. The

developed formulas can be used to estimate the ID effect. However, for simplicity, the live load design moment of interior girders can be increased by five percent to maintain the same safety level as that with IDs, which will in most cases result in one or two extra strands per girder. When the DOTD becomes more confident in completely eliminating the IDs, then the increase of live load will not be necessary.

5. In rating existing prestressed concrete bridges with IDs, if the interior girders are 5 to 10 percent underrated, the developed formulas can be used to account for the beneficial effects from IDs, which will result in some unnecessary load posting.

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INTRODUCTION

Intermediate Diaphragms (called IDs hereafter for convenience) and bridge decks are the two major transverse components that connect adjacent longitudinal girders. The benefits and liabilities of using IDs are much debated, and the topic is controversial. There are many arguments in favor of using IDs because they can *[2]*:

- Transfer lateral loads to and from the deck;
- Distribute vertical live loads between girders, thus reducing maximum deflection and moment for each individual girder;
- Provide lateral supports to girders during construction; and
- Distribute lateral impact loads from over-height trucks to all girders, thus reducing the total damage.

However, there are also many other arguments in favor of eliminating the IDs because:

- Using IDs increases the cost and time of construction;
- Instead of limiting damage from over-height truck, IDs may actually spread the damage, according to some studies; and
- Some analytical results show that IDs do not necessarily reduce the controlling moment in girder design.

Based on a survey conducted by Garcia *[2]*, 8 out of 51 states and regions do not require IDs. Currently, Texas has eliminated the practice of using IDs. In Florida, diaphragms are not required for non-skewed bridges. In Iowa, reinforced concrete (RC) IDs are used where traffic flows under the bridge, and steel diaphragms are used in prestressed concrete (PC) bridges where there is no traffic flowing under the bridge *[3]*.

According to the current LADOTD Bridge Design Manual, the ID requirement (with a typical detail in Figure 1) is related to the span length L as:

- For $L \leq 50$ ft., no diaphragm is required.
- For 50 ft. $< L \leq 100$ ft., one diaphragm is required.
- For $L > 100$ ft., two diaphragms are required.

The AASHTO Standard Specifications *[1]* recommend that IDs be used at the point of the maximum positive moment for spans in excess of 40 ft. While it is stated in the AASHTO LRFD Specifications *[4]* that IDs can improve live load distributions, this effect is not included in the AASHTO design specifications. In the AASHTO Standard Specifications, section 8.12.1 for reinforced concrete and 9.10.1 for prestressed concrete allow omitting IDs where tests or structural analyses show adequate strength. In the AASHTO LRFD Specifications, Article 5.13.2.2 has a similar statement allowing the omission of the IDs if tests or structural analyses show them to be unnecessary.

In summary, due to the high labor cost of cast-in-place concrete diaphragms in prestressed concrete bridges, the use of IDs is considered as an added cost to the bridge construction. Therefore, their applications need to be justified. Since the benefits of using IDs are still controversial and each state has its own policy, further investigation is needed. This is a nationwide issue and a particular area of concern in Louisiana where more economical bridge construction is needed.

OBJECTIVE

The objectives of this research were: (1) to assess the need for IDs in concrete highway bridges and (2) to investigate the use of steel diaphragms if their need is justified.

These objectives were achieved by focusing on Louisiana practices, synthesizing previous nationwide research results, and developing a comprehensive plan to provide supplemental information to reach conclusions and recommendations. Both finite element analysis and experimental research were conducted. The ultimate objective is to eventually achieve more economical bridge construction in Louisiana, while meeting the construction, serviceability, and strength capacity requirements of the code specifications.

SCOPE

This study was limited to simply-supported and continuous straight slab-on-girder bridges, both with and without skew. This study considered only the common type of AASHTO girders and Bulb-T sections with the dimensions specified in the Louisiana Bridge Design Manual. This bridge type consists of the majority of bridge inventory. Box girder and curved girder bridges were excluded from this study, as they have special requirements regarding IDs.

One of the important components of the current study was to determine the effect of diaphragms on the vertical live load distribution of the bridges. The influence of IDs on load distribution was not included in the AASHTO LRFD, as the effectiveness of IDs has been controversial. The lack of a uniform practice and policy regarding IDs among different states and their dependence on various bridge parameters are less understood. Therefore, in order to understand the influence of various parameters on load distribution, a parametric study was conducted. Bridges of various configurations were analyzed, and the results of these analyses have been used to deduce formulas for the influence of IDs on load distribution.

The diaphragm's connection to girders is a cold joint with the connection through rebars. Because of the possible cracking at the ends of diaphragms at higher loads, the entire section does not contribute to the stiffness, thereby reducing the effectiveness of diaphragms. In the past, no significant work has been done to quantify the stiffness contribution of diaphragms in load distribution. In this work, a relation between the effective stiffness of diaphragms influencing the load distribution and the LDF was developed.

An alternative configuration of steel diaphragms that could potentially replace the reinforced concrete (RC) IDs and provide stiffness greater than the target stiffness value was determined. The target stiffness value was taken as 40 percent of the absolute stiffness of RC diaphragms. The configurations of steel IDs where channel section placed horizontally connecting the girder webs and X type bracing with a bottom strut based on girder geometry were considered. The stiffness contribution of these steel diaphragm configurations was calculated, and their influence in load distribution was also determined.

Along with this work, researchers assessed how different diaphragms affect bridge performance under the impact of over-height trucks at the bottom of girders. Also, design forces developed in the steel bracing members during deck construction were determined by performing a finite element analysis using a 3-D solid model to check whether the bracing members could carry the loads coming into it during construction.

End diaphragms have almost always been used in practice; therefore, they were included in the model. The continuity diaphragms for continuous spans have been included in the finite element models.

High strength concrete bridges are becoming increasingly popular. High strength concrete materials were thus included in this study, not in a systematic manner, but rather in a selected and limited number of analysis cases. Including high strength concrete in the finite element analysis will help make more systematic recommendations for IDs, as was rather easily done in the numerical analysis.

Since the study's objective was to investigate the relative effect of IDs, only truck load HS20 was applied to the finite element model, i.e., the lane loads were ignored. The results should be valid for both AASHTO LRFD and standard codes. For the purpose of realism, the Chart for Span Range Limit for Precast Prestressed Girders in the LADOTD Bridge Design Manual was used to set up the bridge parameter ranges.

METHODOLOGY

In this work, two finite element models were used. A simplified 3-D model developed in GT-STRUDL was used to perform the parametric study in determining the effectiveness of IDs in load distributions for various bridge configurations. The use of this model was limited to cases in which the loading was vertical. In cases that needed a more refined analysis or required analysis for lateral loading, a 3-D solid model built in ANSYS was used.

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. All these parameters were varied to observe the influence of each parameter on the load distributions and on the effectiveness of diaphragms. For a successful study, numerous cases of bridges and loading configurations are required. The parameters in this study were suitably chosen from the possible range of these variables so as to quantitatively represent the bridges of all the configurations in the defined range.

A typical two-lane highway bridge with two shoulders was considered in the entire study. The width of the bridge was taken as 50 ft., with each lane, shoulder, and cantilever being 12, 10, and 3 ft., respectively. For placing the loading system close to the edge, an 18 in. thick barrier was assumed along the edges, but these barriers were not considered in the actual design of the bridge. The slab thickness was taken as 8 in., and the compressive strength of concrete for slab and diaphragm was taken as 3,500 psi. Parameters involved in the study are as follows:

1. Four types of girders, AASHTO Type II, III, IV, and Bulb T, were chosen, as these are the predominantly used prestressed concrete girders in Louisiana.

2. Normal concrete compressive strength in the girder was taken as 6,000 psi, and for high strength concrete, this was taken as 10,000 psi. For all the configurations of bridges, an analysis was performed using normal concrete compressive strength while the study on the influence of using girders of high strength concrete was limited to a few cases.

3. The girder spacings of 5 ft. and 9 ft. were chosen; these are the minimum and maximum spacings specified by the LADOTD Manual *[29]*.

4. The minimum and maximum values of the span length for each type of girder were chosen as specified in LADOTD Manual with slight modification.

5. All bridge configurations were analyzed without IDs and then with IDs. The number of IDs was chosen based on the LADOTD specifications.
6. In addition to analyzing right bridges, skew bridges with skew angles of 30^o and 50^o were also analyzed.
7. Continuous bridges were also considered in the analysis.
8. For a limited number of cases, an analysis was performed for bridges with different steel diaphragm configurations.

At the locations of supports for all the bridges considered in the parametric study, end diaphragms were provided parallel to the direction of support. The end diaphragms extend from the bottom of the slab to the bottom flange of the girders. All the RC diaphragms were considered to be eight inches thick.

For bridges with a single diaphragm, the ID is provided at the midspan, and for bridges with two diaphragms, IDs are located at one-third the span length. The current practice in Louisiana is to connect girders through IDs in the region of the girder web height, and the same was adopted in modeling the bridges.

In the case of skew bridges, ID construction is a difficult task and there are various possible geometric configurations of IDs in skew bridges. The diaphragms can be parallel to the support, perpendicular to the girder line, or perpendicular to the girder line but discontinuous with the staggered IDs to maintain equal distances from the support. The third type of configuration described above is predominantly used in Louisiana; hence, this configuration of IDs has been used for modeling diaphragms in skewed bridges. For small skew angles, the orientation of IDs does not influence the results since the distance between the positions of IDs for different configurations would be small.

One of the objectives of this current project is to search for alternative steel configurations which could replace RC diaphragms, if found to be effective. Therefore, a parametric study is made by analyzing bridge configurations where appropriate steel diaphragms were chosen for the corresponding bridges.

An HS-20 standard truck that is a common truck used for design loading was used to load the bridge. The lane loading was not considered in this study, since the difference between the load distribution of lane and truck loading is insignificant, as observed by previous researchers *[25-27]*. Meanwhile, Barr et al. *[15]* concluded that using truck load distribution for lane load is more conservative. Therefore, only the effect of truck loading on the bridges was studied. This is also consistent with the methodology used in developing the AASHTO LRFD *[4]* Code Specifications where only truck loads were considered in determining the Load Distribution Factors (LDFs).

A comparison was done between the two models for the same bridge and loading configurations. The writers observed that the effects of IDs on load distribution obtained from the two models were the same. This has provided the confidence that the simplified model can be used in determining ID influence on bridge performance.

Researchers conducted field inspection and evaluation of typical IDs used in concrete highway bridges in Louisiana. These inspections focused on the connections where cracking is possible, and the overall bridge conditions were evaluated. Some of the bridges inspected were built according to the old LADOTD manual, in which IDs and end diaphragms had exactly the same dimensions, going all the way from the middle of the bottom flange to being connected to the deck. Others were built conforming to the new recommendations, in which the IDs are connected only to the web of adjacent girders.

DISCUSSION OF RESULTS

It is observed that the connection between the girder and the diaphragm is essentially a cold joint and is structurally “weak” with usually one or two reinforcement bars connecting these elements. In past studies, researchers have modeled diaphragms differently and considered different levels of stiffness contribution of diaphragms. This could be one of the reasons for reaching contradictory conclusions and different measures of diaphragm effectiveness in these studies. Hence, the need exists to model the diaphragm rationally to simulate the actual behavior. Otherwise, the diaphragm’s effectiveness may not be appropriately estimated.

Two bridges were considered in which the diaphragms were modeled differently to understand clearly how a difference in modeling the ID affects the bridge behavior. For all the cases, strain, deflection, and load distribution factor from the finite element model, AASHTO STD, and LRFD and the strains in diaphragms were calculated. The results indicated that modeling the diaphragm differently yielded different results.

Preliminary Studies

There is a possibility that the parameters adopted for carrying out a parametric study might not have an appreciable effect on ID effectiveness. Analyzing the bridges for all values of parameters proposed, which have no influence on ID effectiveness, would be unnecessary. To avoid this, a preliminary study analyzed a limited number of cases with a very large increment of each parameter so as to cover its entire range of values to determine a parameter’s influence on bridge performance. A conclusion on whether the parameter has a significant influence on bridge performance was reached based on the results obtained through these studies. If the influence of a parameter was found to be appreciable, then further analysis was done for the remaining cases involving this parameter; otherwise, the parameter was not subjected to further study.

From the results of the preliminary study, span length, spacing, and skew angle were considered as the parameters for detailed parametric study. It is noted that the girder spacing, though not a significant parameter based on the preliminary analysis, is kept for further study for the reasons described earlier.

Formula Development for Determining the Effectiveness of Diaphragm

One of the important objectives of this research was to develop correction factors for LDFs to account for the influence of diaphragms on load distribution. This section discusses the deduction of the formulas to calculate the diaphragm effect on load distribution based on the results obtained from the parametric study and the accuracy of these formulas developed.

When these correction factors are multiplied by the LDFs that were obtained without considering the diaphragm, it gives LDF values that account for diaphragm effects. This is given by the expression ((LDF value $_{\text{without ID}}$ - LDF value $_{\text{with ID}}$)/ LDF value $_{\text{without ID}}$)* 100, and this value hereafter is referred to as R_d.

The final set of formulas can be put together in four equations, with one and two diaphragms for both interior and exterior girders. These expressions for R_d and the variables associated with R_d are listed in Tables 1 to 3.

Table 1
Expressions for R_d value 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	$(-0.112*L +25.81) * C*S_k* S_t$
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 2
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	$1-0.015*\theta$ $(\theta \leq 30^o)$ $0.775 - 0.0075 * \theta$ $(\theta > 30^o)$	$0.0264*X^{0.8062}$	$1-0.01* \theta$ $(\theta \leq 30^o)$ 0.7 $(\theta > 30^o)$	$0.45+0.55* d$ $(0 \leq d \leq 3ft)$
2	$1-0.0167*\theta$ $(\theta \leq 30^o)$ $0.725 - 0.0075 * \theta$ $(\theta > 30^o)$	$0.0873*X^{0.5358}$ (Type IV) $0.3024*X^{0.2641}$ (Type BT)	$1-0.013* \theta$ $(\theta \leq 30^o)$ 0.6 $(\theta > 30^o)$	$0.45+0.55* d$ $(0 \leq d \leq 3ft)$

Table 3
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 Tables 1 to 3:
L= length of the girder in ft.
C = constant
R_d = percent 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 and 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 = (possible diaphragm stiffness contributing to load distribution/absolute diaphragm stiffness)*100

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

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

Where

$(LDF)_{WD}$ = Load distribution factor for bridge, including diaphragm effectiveness in load distribution

$(LDF)_{ND}$ = Load distribution factor for bridge without considering diaphragm effectiveness in load distribution

The accuracy of the formula developed was determined by comparing the R_d values obtained from formula deduced earlier to the R_d values obtained from analysis for a few bridge configurations. The results indicated that the formula developed are accurate since the difference in these values was less than one percent for most of the cases.

Steel Intermediate Diaphragms and Lateral Loading

As mentioned earlier, one of the important objectives of the project was to identify steel diaphragm configurations that could have similar performance as that of RC IDs in PC PS girder bridges, as it would be more economical to provide steel IDs. Diaphragm configurations were chosen based on the geometry of the girder section. For girder Types II, III, and IV, since the depth of the web region of the girders is small, a channel section is appropriate to fit in the girder web region. For a BT girder, the possibility of providing a channel and X type bracing with a bottom strut was explored.

For the BT section, the depth of the web was 54 in., making the concrete section area 432 in.^{2}. This means that to provide a stiffness equivalent to about 40 percent of the axial stiffness of the RC diaphragm, a steel section of 20 in.^{2} would be required, which no single steel section can provide. Also, since the channel depth was small compared to the depth of the 54 in. web, the lateral stability provided by this section might not be adequate for BT girders. Providing an X type bracing with a bottom strut for BT bridges seemed to be a possible alternative. Initial study was done by choosing an MC8x20 channel section for all its bracing members.

One of the reasons for providing diaphragms is to provide stability to girders during deck construction. During this process, the concrete in the deck, being wet, cannot transmit lateral loads that are induced during the construction process and other sources of lateral loading. The diaphragms are provided to transfer these loads from one girder to another and to provide lateral restraint. The present study was limited to comparing the stability provided by steel diaphragms relative to that provided by RC diaphragms rather than determining the absolute stability provided by each of these diaphragms. This was achieved by comparing the principal tensile stresses developed in the girder web region for the bridges with different ID configurations. This analysis was done using a 3-D solid FEM model built in ANSYS.

Assessing the Influence of ID in Limiting Impact Damage of Over-height Trucks

In many instances, prestressed concrete girder bridges have collided with over-height trucks passing under them. The effectiveness of diaphragms in limiting damage during collision is controversial. To get a better understanding of this issue and to know how different diaphragms affect the performance of bridges during collision, an analytical study was carried out with a 3-D solid model built in ANSYS. Simulating the actual collision is a difficult task and beyond the scope of this study. This study was limited to the comparison of the relative performance of bridges with different diaphragm configurations under lateral impact loading, which was applied as a concentrated static load.

The study of impact on bridge behavior with different ID configurations was done for two bridges. The two bridges chosen were S9L90 and S9L130, for which the study was done with steel ID, RC ID, and without ID. Steel ID configurations used for S9L90 and S9L130 were channel section and X plus bottom strut, respectively, as proposed earlier. For X plus bottom strut diaphragm members, the elements were modeled as 3-D LINK-8 elements (line element), while a channel section diaphragm was modeled as SHELL 28 elements (two dimensional shell elements) in ANSYS.

The magnitude of impact is a function of several parameters such as mass, speed, geometrical configuration, and hardness *[12]*, and there is no available literature which gives information on issues related to impact loading. A numerical value of impact load was assumed, which was applied as a concentrated static load. This value was taken as 120 kips, the same value which was used by Abendroth et al. *[12]*. This study was done for impact at the bottom flange of the girder.

For both bridges, the impact load was applied at two locations - one at the location of the ID and another midway between two diaphragms. For S9L130, where there are two diaphragms, impact load was applied midway between the two IDs (which is the midspan) and at one of the IDs. For S9L90, the loading was applied midway between the ID and the end diaphragm (one fourth span length) and at the location of the ID (midspan).

From the results obtained in these two bridges, it can be observed that when the impact occurred at the location where IDs are located, different IDs reduced the impact stresses to a different extent with respect to the case without IDs. Since the magnitude of the real future impact load is unknown, it could not be concluded if the diaphragm would be in a position to transfer the impact load successfully to other girders, as the structural performance may be nonlinear under large impact loads. A more detailed study is needed to reach a conclusion on how diaphragms affect the performance of a bridge when the impact occurs at the location of the diaphragm. But when the impact takes place at a significant distance from the ID, the ID and its type have no effect on the behavior of the bridge under impact. If the IDs are provided for the purpose of protecting the girders under impact, they must be provided above each lane of the road under the bridge. Therefore, the current ID locations that are based upon the purpose of providing stability are not sufficient for protecting the girder under impact.

After selecting the diaphragms and confirming that those diaphragms chosen were adequate, a parametric study was carried out for the bridges with corresponding steel diaphragms for those bridges. By comparing the R_d values obtained from the FEM to those obtained from the formulae, it was concluded that the R_d formula developed for RC diaphragms could be used for steel diaphragms also by taking the axial stiffness ratio of steel to RC ID into consideration in determining the stiffness reduction factor.

Discussion of Experimental Results

The research team conducted static and dynamic load tests on the selected bridge structure on February 20, 21, and 22, 2006. The tested bridge is located over Cypress Bayou in District 61, on LA 408 East. The location of this bridge and its easy accessibility were some of the factors that were considered. The total average daily traffic (ADT) for the structure was 11,473 according to its last bridge inspection data recorded on March 11, 2002. This bridge structure is representative of the large majority of prestressed concrete slab-on-girder highway bridges in the state of Louisiana and was selected by an inspection team comprised of personnel from FHWA, LADOTD, and LSU's research team.

Strains were acquired by a 16-channel Structural Testing System II (BDI-STS II) manufactured by Bridge Diagnostics Inc. Acoustic emissions were acquired using a state-of-the-art DiSP Acoustic Emissions workstation system along with a set of four Physical Acoustics Corporation (PAC) sensors to facilitate non-destructive inspection of structures. These sensors were used to detect cracking on both sides of the middle girder and intermediate diaphragm. The bridge was loaded with two dump trucks weighing 61.1 kips (Truck 1) and 61.3 kips (Truck 2). Their weights were acquired using portable scales. The weight values in the front axles were 18.0 kips and 17.8 kips, with back axle weights equal to 43.1 kips and 43.5 kips, respectively.

Dynamic loading tests were performed on traffic lanes with the truck at speeds of 30.0, 38.5, 40.0, and 43 mph. In addition to strains, deflections, and acoustic emissions, accelerations were also continuously acquired as the truck passed over both traffic lanes at the above-mentioned speeds, one lane at a time.

Comparisons of strains, deflections, and load distribution factors (LDFs) for the results obtained from a few loading tests were used to calibrate the finite element model. In general, the measured results (strain and/or deflections) were less than finite element predictions and AASHTO code specifications because there are many field uncertainties for field bridges. For instance, the connection between diaphragm and girders may not be fully rigid, and the real stiffness contribution of ID is not known. Some research shows that the actual diaphragm stiffness contribution is about 30 percent of its whole section stiffness. Another reason for the difference between predicted and measured values is the actual concrete strength, which is usually higher than that specified in the project plans because concrete hardens as it ages, and most concrete is cast higher than the specified strength. Therefore, actual concrete strengths 30 percent higher than design strengths are very possible. Real support conditions are also in question. The anchor bolts may provide some constraints to the bridge that render the pin-roller type of beam model inaccurate.

As a first try, the finite element predictions were closer to these field data when the overall concrete stiffness was increasing by 30 percent, while reducing the concrete for the intermediate diaphragms to 30 percent. While the concrete stiffness increase is easily explained by the concrete strength increase with time, the ID concrete stiffness reduction is more complex. The ID connection to the girders and its lower concrete stiffness are some of the logical reasons, since the concrete ID was cast-in-place with lower strength after the concrete girders had reached their full design strength. The intense vibration caused by heavy trucks at high speeds may result in cracks at the diaphragm-girder interface that is actually a cold joint, which is another reason for the ID effectiveness reduction, as shown by the results comparison.

The comparisons below indicate that the ID stiffness has to be considerably decreased so that the finite element results match the field tests, which seems to be acceptable due to the reasons mentioned above.

Nonlinear Analysis

In the current practice, LDFs calculated according to AASHTO LRFD *[4]* yield linear results, which theoretically correspond to service loadings. To better assess the condition of existing and new bridge systems, it is necessary to understand how bridges would behave under loadings beyond elastic ranges. The knowledge of how live loads are distributed beyond the elastic range will increase engineers' ability to evaluate the condition of both existing and new bridges using predictive analysis. Particularly for the present study, a nonlinear analysis would help researchers understand the real capacity of the prestressed bridges, especially if the IDs were eliminated. Comparisons of load distributions were performed using the strains, deflections, and section moments obtained using a full 3-D finite element analysis of the tested bridge.

Cost Analysis

According to the research results discussed earlier, when considering rigid connections between the IDs and the girders, removing IDs should benefit the exterior girders by reducing their LDFs, but it will actually increase LDFs up to about 15 percent for the interior girders. However, this could be a fictitious number since the real connection is much weaker. Previous literature suggested that the IDs contribute about 30 percent of their stiffness. This conclusion was confirmed by the present experimental results. Therefore, the maximum ID effect on load distribution should be at a level of five percent. In Florida, a five percent live load increase for prestressed concrete girder design is specified for the cases in which the IDs are eliminated to compensate for their contribution to the load distribution. As discussed earlier, the ID contributions to the load carrying capacity are not explicitly considered in the bridge design codes *[1, 4]*; therefore, they can be theoretically eliminated without affecting the design process. However, the safety will be reduced for interior girders. To make up this reduced safety factor, design engineers may consider increasing the live load by five percent or ten percent as Florida has done. To investigate the impacts of this increase on bridge design, 15 cases were designed ranging from Type II to BT beams to cover a wide range of typical girder designs.

By increasing the live load by five percent, most girders end up with an increase of one strand, and the maximum is two strands. By increasing the live load by 10 percent, most girders also end up with an increase of one to three strands. The cost of concrete diaphragms depends on the location and quantities. It varies from $448 to $1,450 based on some information from LADOTD bidding records. Since there are no steel diaphragms used for prestressed concrete bridges in Louisiana, there are no bidding records for this type of diaphragm. However, the price for steel diaphragms for steel bridges is used in the calculation. The initial prices for both steel and concrete diaphragms are extremely close. However, when making the decision to choose the diaphragm type, we need to consider the fact that steel diaphragms, while they can shorten the construction time, may require additional maintenance work due to corrosion issues.

SUMMARY AND CONCLUSIONS

This report presented the methodologies, findings, and results from the entire process of this project.

1. The research team examined and reviewed the state-of-the-art technology and current practices from many sources regarding intermediate diaphragms. Current Louisiana practice was investigated through a survey sent to all nine LADOTD districts, a review of the Louisiana Bridge Design Manual and other technical literature, and direct interaction with experienced bridge engineers. Bridges that were of interest for this study were selected for visiting and field inspection. Much information was acquired from these field trips to various bridge locations.

2. A refined scope of work was developed through a work plan. The parametric study was conducted successfully, and important parameters were identified to understand how each one influences the ID performance on the load distribution factor. From the initial parametric study, it was concluded that the ID influence on bridge performance was mainly a function of span length, skew, diaphragm stiffness, and location of diaphragms, and was found to be relatively independent of continuity, girder spacing, and number of spans.

3. Through further analysis of the identified parameters, the effect of IDs on load distribution was quantified. The current AASHTO design codes do not include information about quantifying the ID performance in load distribution. A systematic parametric study was carried out using a wide range of values for possible parameters which were representative of the current prestressed concrete girder bridges existing in Louisiana. From the results obtained through this parametric study, formulas were developed to determine the diaphragm effect on load distribution for both interior and exterior girders.

4. Using the correction factors developed to account for the influence of IDs, a more rational load distribution factor could be obtained. The formula developed for an increase in load distribution due to the ID effect on exterior girders gains importance, as no rational formula is available for determining this increment in LDF due to IDs.

5. From the results obtained in the parametric study and the formulae developed, it could be concluded that the ID decreases the load distribution factor for interior girders and increases the load distribution factor for exterior girders. The IDs increased the deflection marginally for exterior girders and decreased the deflection for interior

girders. The deflections were observed to be within permissible limits, both with and without IDs, thereby indicating that deflection is not an important criterion influencing the decision to eliminate RC IDs or replace them using steel IDs.

6. Researchers proposed steel diaphragm configurations for different bridge configurations that could perform similarly to RC diaphragms. A study was done on the relative performance of RC IDs and steel IDs during the process of deck construction. The alternate steel diaphragms were proposed based on the minimum target stiffness as a proportion of the absolute diaphragm stiffness contributed by the existing RC ID. These steel IDs were found to provide stability near that produced by RC IDs during the deck construction. Therefore, if the reinforced concrete diaphragms were provided only for the purpose of providing girder stability during construction, then this could be served by providing steel diaphragms.

7. Reinforced concrete IDs and steel IDs under lateral impact loading were investigated, keeping in view the possible collision caused in the prestressed concrete bridges due to over-height trucks passing under them. Through these studies, various issues relating to ID effectiveness were covered to assess the need for reinforced concrete intermediate diaphragms, and alternate ID configurations were proposed.

8. Results obtained from the impact tests carried out on the bridge with different ID configurations indicated that RC IDs provided the greatest protection to exterior girders undergoing impact, when the impact occurred at the ID location. When the impact took place at a location away from the ID, it was observed that the ID configuration did not significantly influence the bridge performance. The researchers concluded that the IDs could not be counted on for their ability to protect girders if the IDs were not right above the traffic lanes. In cases where there is no traffic passing under the bridge, steel IDs could be used as well if their only purpose is to provide stability.

9. Based on the nonlinear finite element analysis, the ultimate strength calculated according to the current AASHTO LRFD code is very conservative. This means the strength of the bridge is underestimated when the actual strength is almost double that predicted by the code. Therefore, generally speaking, the ultimate strength of prestressed concrete bridges should have no problem, even without IDs, if the code specified capacity is satisfied.

10. Detailed descriptions of the field testing were presented. Strains, deflections, and acoustic signals were acquired. Preliminary analysis showed that when 30 percent diaphragm stiffness was considered, it resulted in a better match with experimental

observations than when the full stiffness was used.

11. When considering rigid connections between the IDs and the girders, the maximum effects of IDs on load distribution was up to 15 percent, except for BT beams that can be as high as 26 percent. However, this could be a fictitious number since the real connection is much weaker. Previous literature suggests the IDs contribute about 30 percent of their stiffness. This conclusion was confirmed based on the observation of the present experimental results. Therefore, the maximum effect of ID effect on load distribution is at a level of 5 percent for most beams and 10 percent for BT beams.

RECOMMENDATION FOR IMPLEMENTATION

As in the case with many engineering issues, there are no simple yes or no answers. Therefore, the recommendations are made under different given conditions and the engineer can make decisions based on the given conditions:

1. If sufficient supports, either temporary or permanent, are provided during construction, and over-height truck lateral hitting is not the concern (such as the cases where there is no traffic underneath the bridge), IDs can be eliminated. In terms of vertical live load distribution, IDs are beneficial to interior girders but harmful to exterior girders. The current AASHTO load distribution factor is conservative and provides adequate strength for the code specified live load, even though IDs are not used.

2. If IDs are to be provided to protect against lateral impact, they should be placed as close as possible to the locations of possible impact. Concrete IDs are recommended for this purpose since they provide better impact protection than steel IDs. If the impact is not near the ID location, IDs provide no direct protection. However, IDs located away from the impact point may help support the damaged girders.

3. For the purpose of construction stability, steel IDs can be used to replace concrete IDs. Therefore, where collision protection is not required, such as in the case of bridges over bayous, steel IDs can be used in place of the current concrete IDs.

4. If IDs are completely eliminated, there will be an increase of strain action for the interior girders. The developed formulas can be used to estimate the ID effects, i.e., the change of load distribution factor. However, for simplicity, the live load design moment of interior girders can simply be increased by five percent to maintain the same safety level as that of bridges with IDs, which will result in most cases in one or two extra strands per girder. When the LADOTD becomes more confident in completely eliminating the IDs, then the increase of live load is not necessary.

5. If IDs are provided, four continual rebars (instead of one rod) are recommended across the web of the interior girders. A stronger connection between the IDs and girders will reduce the strain in the interior girders. Regarding the exterior girder, we may keep the details the same as the current practice for two reasons. First, anchoring rebars to the web of exterior precast girders will increase cost (maintenance and construction). Second, a stronger connection will put more loads on exterior girders. Using a weak connection is beneficial to exterior girders.

6. In rating existing prestressed concrete bridges with IDs, if the interior girders are five to ten percent underrated, the developed formulas can be used to account for the beneficial effects from IDs, which will result in some unnecessary load posting or strengthening of bridges.

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