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Field Investigation of Post-Tensioned Box Girder Anchorage Zone

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ABSTRACT

Adequate anchorage zone performance is critical for proper performance of post-tensioned bridges. Post-tensioning anchorage zones of box girder bridges need to have adequate reinforcement and proper concrete placement. It is essential that sufficient reinforcement be provided to handle the spreading of forces in the general zone of the end anchorage. It is also critical that concrete stresses remain sufficiently low to prevent crushing, especially in areas immediately ahead of the anchorage device and at changes in geometry. Current design methods have led to highly congested anchorage zones with construction issues and cracking problems.

In order to study the performance of anchorage zones, end diaphragms of box girders were instrumented in the field. Different types of strain gauges were used in order to capture strains on reinforcing bars, and within the concrete elements. The field investigation enables the measurement of the actual flow of strains in the structure. Through these strains, the flow of forces was determined. Finally, developing realistic models are needed to understand the behavior of anchorage zones, determine the actual safety margin during construction, estimate minimum requirements for elements' dimensions and calibrate the adequacy of existing amounts of reinforcement.

KEYWORDS: *Anchorage Zone, Field Investigation, Post-tensioned Box Girder, End Diaphragm.*

1. INTRODUCTION

Construction issues and cracking problems occurred in anchorage zones of box girder bridges. These local problems affected the global performance of box girder bridges. Current design codes do not provide a clear method for design of anchorage zones at the end diaphragm. Available design equations can be used only for rectangular sections. In the case of a box girder, the cross section changes from a rectangular section through the diaphragm to an irregular shape at the webs of the box girder. In order to prepare convenient instrumentation plans, preliminary finite element models were developed. These models were used to determine the critical locations for instrumentation of the anchorage zone of box girders. The instrumentation procedures were different depending on each individual case of construction and dimensions of the end zone of a box girder.

The main criterion in the field instrumentation was not to make an obstacle in the time schedule of the bridge construction. Several safety cautions were considered to make sure the instrumentation is not interfering with construction. Three box girder bridges with different configurations were instrumented. Finite element models for the instrumented bridges were developed to assess the excepted performance of the anchorage zones.

2. PROBLEM STATEMENT

Anchorage zones need to have proper reinforcement and proper concrete placement. Construction issues and cracking problems occurred in anchorage zones of box girder bridges. A box girder bridge with 350 cm depth was affected by significant cracking in the deck and the girders due to post-tensioning. The anchorage zone is considered a local part of the bridge, but inadequate design and detailing affects the global performance. This problem was evaluated afterwards using detailed finite element analysis. The recommendation of that analysis was to increase the thicknesses of end diaphragm and web flares. Another problem that occurs in box girder bridges during construction is cracks propagate out of pre-stressing block-outs as shown in Fig. 2.1. However, there are no requirements of reinforcement ratios or details in the box girder deck near the end diaphragm due to post-tensioning in any available code or design recommendations.

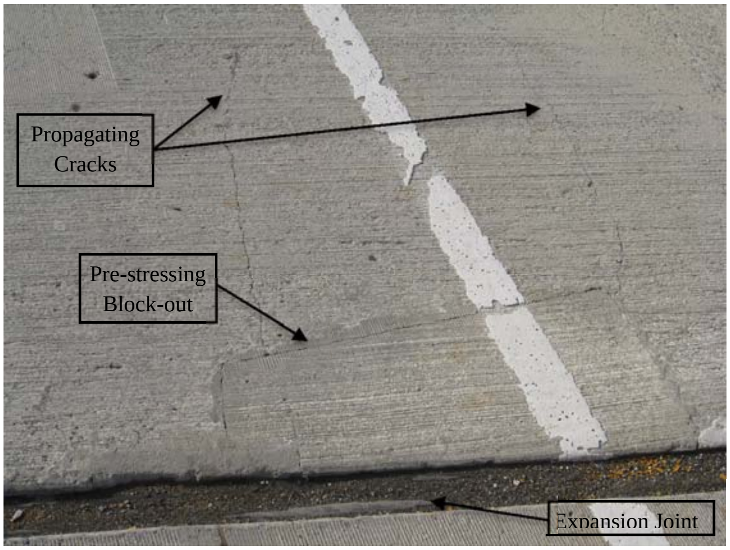


Figure 2.1 Top view for box girder deck illustrating crack propagation from pre-stressing block-out.

Current design methods lead to highly congested anchorage zones. Several design methods are available for design and detailing of anchorage zones. Strut-and-tie method is a convenient way for design of such complex zones, but it needs a lot of iterations in order to obtain a reasonable solution. There are clear strut-and-tie models for problem like: corbels, beams, frame joints, anchorage zones of rectangular cross sections, footings and pile caps [1]; however, the models are not so clear for box girder anchorage zones. New technique was presented by Zhou et al. [2] using iso-static lines or stress trajectories to obtain transverse stresses in end anchorages, but it was applied only on rectangular sections. The elastic analysis method presented by Nawy [3] and Namaan [4] for design of end anchorage is applicable for irregular sections, but it cannot be applied in the case of end anchorages of box girder bridges. In the case of box girder, the cross section changes from a wide rectangular section through the diaphragm to an I-Shape section at the webs of the box girder. Although finite element modeling is a powerful tool, it needs verification before it can be used in design.

Different design codes and guidelines can be used for design of anchorage zones. British Standard BS8110 [5] as well as CEP-FIP 1990 [6] are applicable for the design of end anchorages with rectangular cross sections only. Although, when the end anchorage is as complex as in the box girder, other design codes [7] [8] refer to strut-and-tie method or finite element analysis. Both methods cannot be simply applied, as they need many iterations and verification. Recently, the California Department of Transportation (CALTRANS) implemented an anchorage zone design procedure in Memo to Designers 11-25 Anchorage Zone Design [9]. These procedures included minimum thicknesses for the end diaphragm and the girder web as well as minimum vertical reinforcement in girder webs. On the other hand, no detailed design procedures were presented.

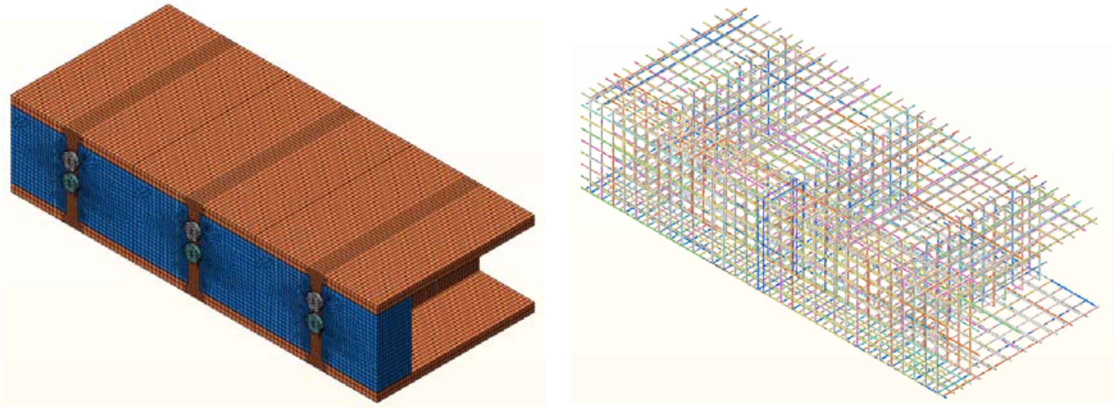
The last substantial experimental research on post-tensioned concrete anchorage zones was done as part of the National Cooperative Highway Research Program (NCHRP) 10-29 [10] which was completed in 1994. Realistic models are needed that provide safe models and reduce reinforcement congestion. The reduction of congestion will improve the chances of having high quality concrete in the anchorage zone and better performance.

3. PRELIMINARY ANALYSIS

Preliminary analysis was needed to determine the critical zones of stress concentration due to pre-stressing. These zones were instrumented in the field in order to measure the actual increase in strains during post-tensioning. Preliminary finite element models were developed for typical end anchorages of a box girder. The second phase of the analysis included preparation of a database for newly constructed bridges. This database was used to identify average dimensions for box sections and typical reinforcement configurations. Also, the developed database provided a good understanding for the existing reinforcement ratios in different locations at the end anchorage of the box girder.

3.1. Finite Element Modeling

In order to determine the critical locations for instrumentations of box girders' anchorage zones, finite element analysis was needed. Finite element modeling of end anchorage is complex due to the geometry of this zone in addition to congested reinforcement. Three-dimensional model for a repetitive girder was developed using DIANA R 9.6 [11] as shown in Fig. 3.1. The mesh of the end diaphragm, girders, soffit, deck and loading plates of the model are shown in Fig. 3.1 (a), and the reinforcement details are shown in Fig. 3.1 (b). The box section had 220 cm height (h), 320 cm spacing between girders (S), 40 cm web width and 90 cm end diaphragm thickness. Two eccentric pre-stressing straight ducts were modeled as voids. The applied load was 7800 kN, which represents 15% of the concrete section axial capacity. Loads were applied on circular loading plates.



(a) (b)

Figure 3.1 Three-dimensional view of DIANA model illustrating (a) concrete mesh and (b) reinforcing bars.

Locations of stress concentration and critical zones were determined using the developed model as shown in the longitudinal section in Fig. 3.2. The transparent parts of the figure represent the compression zones as the tensile vertical bursting stresses are only plotted. It is illustrated from the stress concentration of vertical tensile stresses that the critical zones are the inner face of the end diaphragm and approximately 0.5 h of the web are affected by bursting tension forces. This was the reason that instrumentations were placed in these critical zones only.

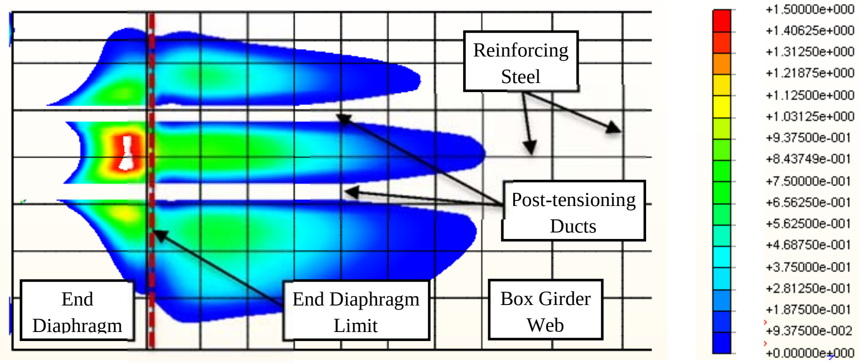
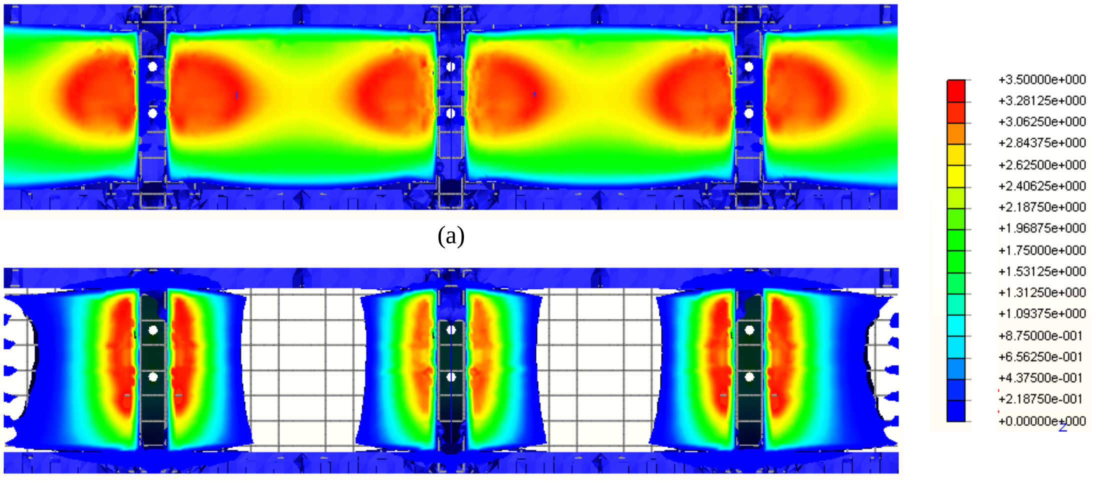


Figure 3.2 Vertical tensile stresses (MPa) of longitudinal section of the box girder.

The vertical and horizontal tensile stresses on the inner face of end diaphragm are plotted in Fig. 3.3 (a) and (b), respectively. The distribution of the vertical stresses illustrates that end diaphragm vertical reinforcement shall be designed for post-tensioned bursting forces. The pattern of the horizontal tensile stresses extends only to 30% of the girder spacing on both sides of the girder. Horizontal reinforcement on the end diaphragm's inner face shall be also designed for post-tensioned bursting forces. As a result of this preliminary modeling, critical zones were determined. These zones were defined by high bursting tensile stresses. In order to check that the newly constructed bridge has special considerations for detailing these zones, a bridge database was developed.



(a)

(b)

Figure 3.3 Inner face of end diaphragm tensile stress (MPa) contours (a) vertical and (b) horizontal.

3.2. Constructed Box Girder Bridges Database

A database for newly constructed bridges was prepared. This database included box section dimensions, end diaphragm reinforcement ratios, end diaphragm width, web reinforcement ratio, cable profile and pre-stressing force. It included 29 bridges with more than 50 end anchorage configurations. This database was used to determine the average dimensions for box sections recently constructed. The typical reinforcement configurations were identified. The developed database provided good understanding for the existing reinforcement ratios in different locations at the box girder end anchorage. In order to determine the criteria of placing reinforcement in the end diaphragm, different reinforcement ratios in the end diaphragm were plotted against pre-stressing jacking force as shown in Fig. 3.4. No correlation was found between any reinforcement ratio and the pre-stressing force. Also, there was wide variation in the reinforcement ratio of each side of the end diaphragm. The vertical stirrup ratio varied between 0.08 to 0.23 % (approximately four times); the reinforcement ratio of horizontal bars on the inner face of the end diaphragm varied between 0.035 to 0.125 % (approximately four times); and the reinforcement ratio of horizontal bars on the outer face of the end diaphragm varied between 0.035 to 0.16 % (approximately five times). These variations explain that placing reinforcement is done more by rule of thumb depending on typical bar diameters used in the end diaphragm, maximum spacing between bars and previous experience. However, no certain design procedures are applied to get the exact amount of reinforcement in the end diaphragm.

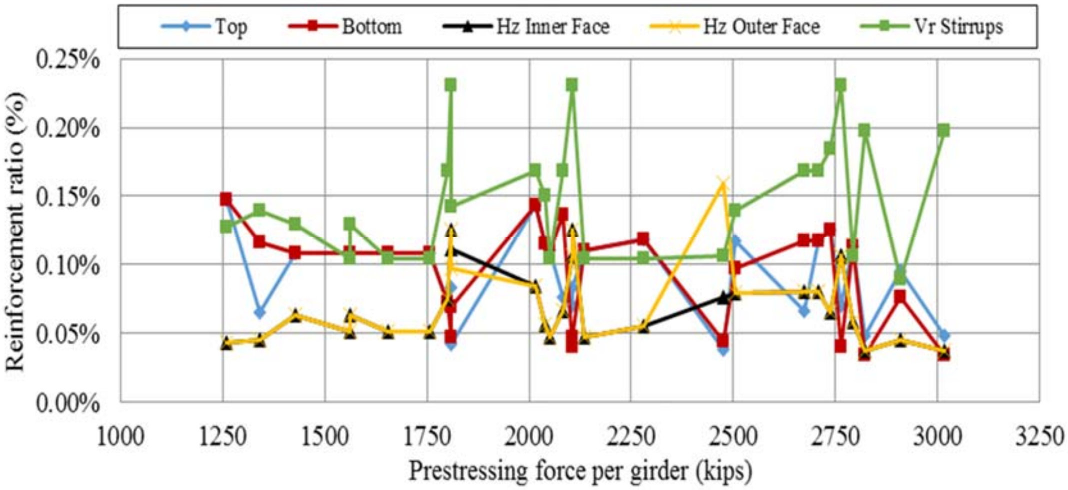


Figure 3.4 Different reinforcement ratios of end diaphragm vs. pre-stressing force.

4. FIELD INSTRUMENTATIONS

The instrumentations were placed in the critical zones obtained from preliminary modeling. Different techniques of instrumentation were investigated until convenient ones were chosen. The primary criterion in the field instrumentation was not to make an obstacle in the time schedule of the bridge construction. Two different types of strain gauges were investigated in order to capture the performance of box girder anchorage zones. The used instrumentation devices were concrete gauges to measure the strains inside the concrete elements and steel gauges to measure the developed strains in reinforcing bars. Attaching strain gauges to the reinforcing bars in the field was nearly impossible, as this process needed accessibility to reinforcing bars and a longer time frame for installation. The construction time schedule would not allow for such delays. So, an alternative methodology was used. Reinforcing bars were prepared with strain gauges in the lab. These bars were named “Sister Bars”. These bars will increase the reinforcement ratio; however, this increase was minimized by using #3 bars (10 mm diameter). The increase in reinforcement ratios in all the instrumented bridges did not exceed 10%, which can be considered as ineffective due to the random values of existing reinforcement as illustrated previously in Fig. 3.4.

4.1. Instrumentations Preparation

Several types of strain gauges were investigated in order to choose the appropriate type for both concrete and steel. The main parameters in choosing convenient strain gauges were accuracy, applicability, level of recorded data, interfering with the construction, safety during construction and sensitivity to concrete placement. For reinforcing bars, foil strain gauges with a maximum strain of 5% was chosen, as the strains in the field will not exceed the yield strain of the reinforcing bars. Strain up to 5% was acceptable. Also, several procedures have been considered to maintain safety of the strain gauge before the pre-stressing process. The reinforcing bars were grinded to prepare the bar surface. Strain gauges were attached using a matching type of adhesive. Thick layer of wax was added above the strain gauge to seal it from water during concrete placement. Certain type of flexible tape was used as additional coating. After that, a thick epoxy layer was added as shown in Fig. 4.1. Due to the severe environment for the reinforcing instrumentation, mastic water sealant tape was used as an additional coating surface for the bars placed in the bridge deck. The concrete gauges were dumbbell shaped. The gauge length was 50 mm and backing thickness was 4 mm diameter. All strain gauge wires were inserted in heat shrink tubes as a coating as presented in Fig. 4.1.

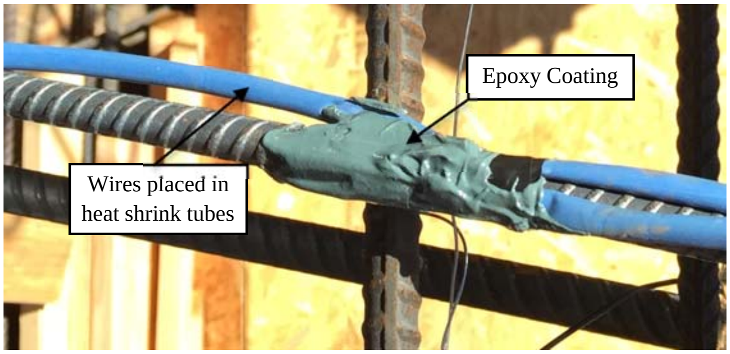
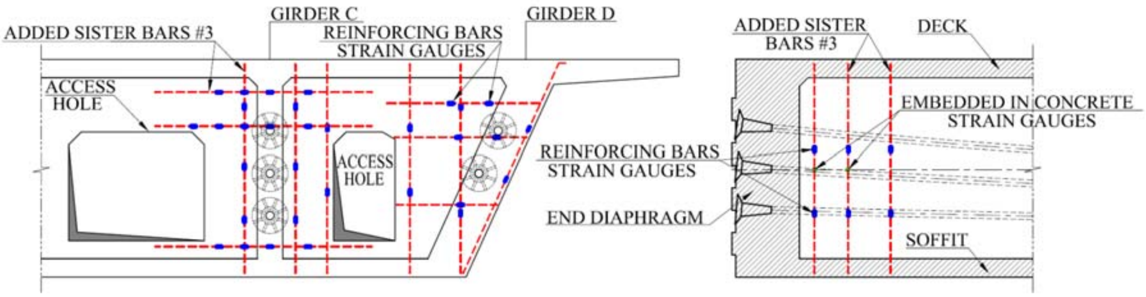


Figure 4.1 Reinforcing bars strain gauges coated with epoxy.

4.2. Instrumentation Plans

Instrumentation plans were prepared to study the performance of the anchorage zone in three box girder bridges. Drawings included the location of strain gauges and sister bars. Fig. 4.2 (a) and (b) show instrumentation in inner diaphragm face and internal web for one of the instrumented bridges. Configurations of the three instrumented bridges are summarized in Table 4.1. It includes bridge type, number of cells, jacking force, box girder height, girder spacing, width of diaphragm, deck and soffit thicknesses, maximum span length and number of pre-stressing ends. Bridges (I) and (II) will be post-tensioned from both ends; however, Bridge (III) will be post-tensioned from only one end. One of the main differences between the instrumented bridges is the configuration of the openings in the end diaphragm. Bridge (I) has access holes between all box webs. However, Bridge (II) has a solid end diaphragm. Only one utility hole is in the diaphragm of Bridge (III). These openings in the end diaphragm will affect the performance of the end anchorage during pre-stressing.



(a) (b)

Figure 4.2 Instrumentation drawings for (a) inner diaphragm face and (b) internal web.

Table 4.1 Instrumented bridges' configuration

	Bridge I	Bridge II	Bridge III
Bridge Type	Straight	Curved	Curved
No. of cells	3	3	5
Jacking force per girder (kN)	12300	8050	12418
Box girder height (mm)	2600	2200	1650
Girder Spacing	3200	3200	3300
Width of end diaphragm (mm)	800	900	1200
Web thickness Internal / External (mm)	300/500	300/500	300/450
Deck thickness (mm)	220	220	215
Soffit thickness (mm)	190	190	190
Max. span length (m)	67.0	50.8	41.9
No. of pre-stressing ends	Two ends	Two ends	One end
Notes	Access holes for all bridge girders	Solid end diaphragm	Utility hole in end diaphragm

4.3. Instrumentations Installation

Installation of the sister bars and the concrete strain gauges was a very important stage. Several safety cautions were considered to make sure the instrumentation was not interfering with construction. Construction workers usually step on reinforcing bars during construction. They even use the horizontal secondary bars as a ladder to climb up and down. Hiding the wires under the reinforcing bars was an important task during placing the strain gauge wires as shown in Fig. 4.3. Concrete strain gauges are very fragile and no coating can be applied to them. These gauges were fixed in place using thin mechanical wires. To prevent damage of such fragile gauges, they were hidden under pre-stressing ducts as shown in Fig. 4.3.

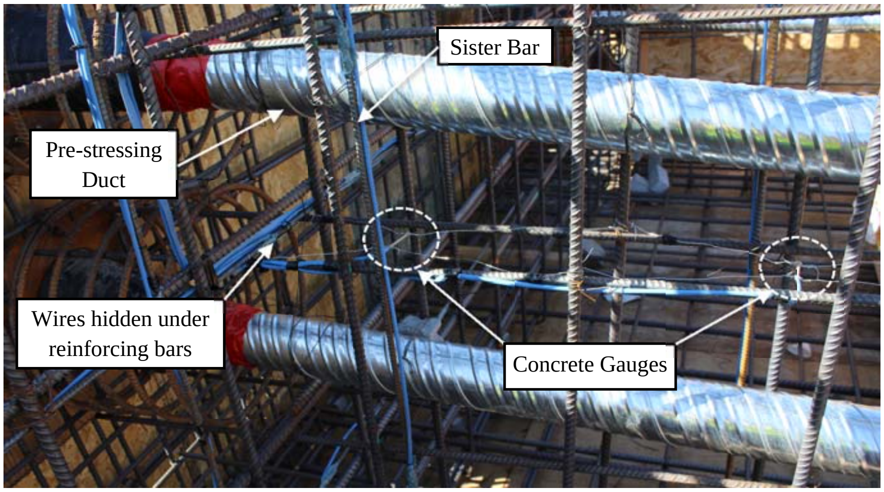
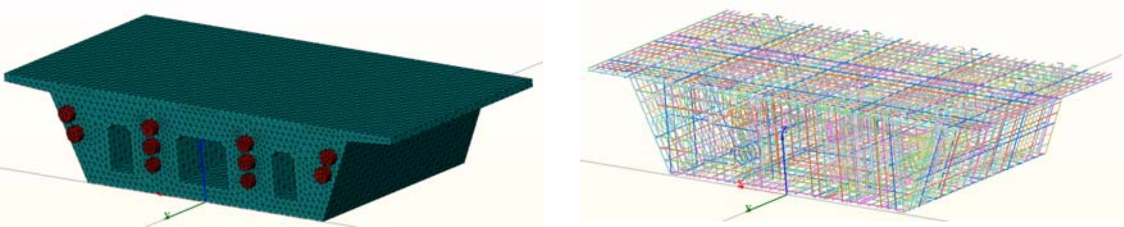


Figure 4.3 Installed instrumentations in the field.

After concrete placement, all strain gauges were checked using a digital ohmmeter. The resistance measured showed that more than 90% of the wires are still connected to the strain gauges installed inside the end anchorage. This check illustrated that the safety procedures used was adequate for field instrumentations.

5. EXPECTED ANCHORAGE PERFORMANCE

Another DIANA model was developed for the end anchorage of Bridge (I). The configuration of the Bridge was illustrated in Table 4.1. The mesh of the box girder and the loading plates of the model are shown in Fig. 5.1 (a) and the reinforcement details are shown in Fig. 5.1 (b). In order to study the effect of the access hole on the performance of the end anchorage, another model with the same exact configuration was developed. The second model had a solid diaphragm instead. The stressing sequence was defined in both models. Fig. 5.2 illustrates the stressing sequence for both bridges.



(a) (b)

Figure 5.1 Three-dimensional view of the end anchorage of Bridge (I) DIANA model illustrating (a) concrete mesh and (b) reinforcing bars.

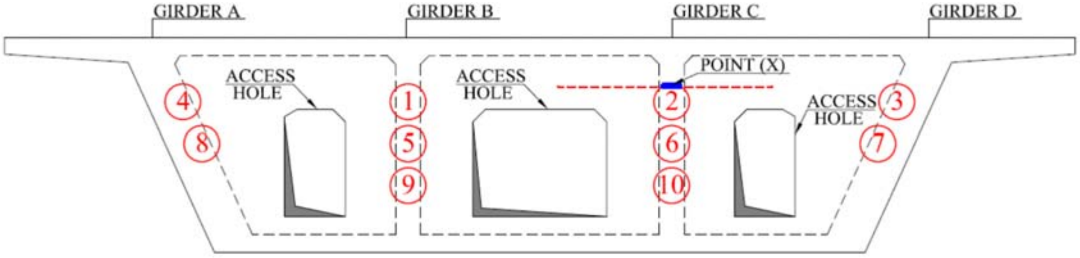


Figure 5.2 Stressing sequence of Bridge (I) first end.

In order to compare the performance, one horizontal instrumentation bar was chosen. This bar was located on the inner face of the end diaphragm just above the pre-stressing duct. The comparison location point (X) was identified in Fig. 5.2. The relationships between the resulted strain of the horizontal bar at point (X) and the total jacking force of the bridge in case of a solid diaphragm and presence of access holes, are illustrated in Fig. 5.3. The different stages of loading depending on stressing sequence are noted at the bottom of the figure in circles.

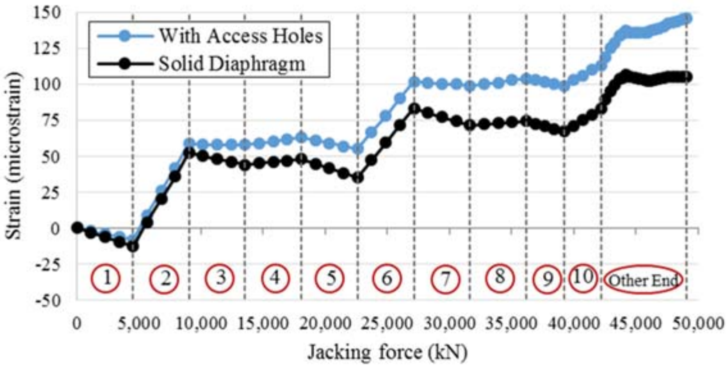


Figure 5.3 Relationship between the resulted strain at point (X) and total jacking force in case of a solid diaphragm and presence of access holes.

From the previous figures, it is noticed that the access holes have a minor effect on the strain in the bar in the low level of stressing up to 10,000 kN. This value represents 20% of the total pre-stressing force. However, the stressing level increases due to the presence of the opening in the diaphragm by 30%. That illustrates the significant effect of openings on the continuity of stresses in end diaphragms as well as the strains and stresses in reinforcing bars.

6. CONCLUSIONS AND FINDINGS

This study investigates the performance of box girder anchorage zones using field instrumentation and finite element models. Three-dimensional models for the end anchorage were developed using DIANA [11]. The following conclusions and findings can be reached from this study:

- Realistic models are needed that provide safe models and reduce reinforcement congestion. The reduction of congestion will improve the chances of having high quality concrete in the anchorage zone and better performance.
- Preliminary finite element models determined the critical zones of stress concentration due to pre-stressing. The inner face of the end diaphragm and approximately 0.5 h of the web are affected by bursting tension forces.
- The developed database for anchorage zones of bridges illustrated wide variation in the values of reinforcement ratios in the end diaphragm. These variations explain that reinforcement placement is more of a rule of thumb depending on typical bar diameters used in the end diaphragm, maximum spacing between bars and previous experience.
- Several issues were considered in choosing the convenient type of strain gauges, suitable coating materials, cover for the gauge wires and installing technique. These safety procedures were adequate for field instrumentations.
- Holes in the box girder diaphragm affect the performance of end anchorage. These holes have significant effect on the continuity of stresses in end diaphragms as well as the strains and stresses in reinforcing bars.

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