EXPERIMENTAL EVALUATION OF BOTTOM FLANGE SPLITTING CRACKS IN I-GIRDERS

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ABSTRACT

To improve the structural efficiency of prestressed concrete highway bridges many state transportation departments, including the Florida Department of Transportation, have introduced new I-girder sections. These sections have relatively wide bottom flanges capable of accommodating more than double the number prestressing strands as comparable AASHTO sections of similar depth. The large quantities of prestressing allow the new girders to span lengths unobtainable with the AASHTO sections. One concern with the new girders, however, is the propensity for splitting cracks to form in the bottom flange at girder ends during prestress transfer. To evaluate this concern, six 54-in. deep Florida I-Beam (FIB) specimens were fabricated and monitored during prestress transfer and during the following months. Variables in the test specimens included: quantity/configuration of confinement reinforcement, presence/lack of steel bearing plates, prestressing strand layout, and partial debonding of up to 45% of prestressing strands. Bottom flange cracks were monitored, recorded, and quantified to determine the effects of test variables. Detailing and design recommendations were made based on the results of the test program. Recommendations will be of interest to engineers and fabricators who work with I-girders having wide and/or heavily prestressed bottom flanges.

Keywords: Pretensioned Girders, Confinement Reinforcement, Bearing Plates, Strand Debonding, Flange Splitting, End Region

INTRODUCTION

In 2009 the Florida Department of Transportation (FDOT) introduced the Florida I-Beam (FIB) series as their standard for prestressed concrete bridges. The FIB girders were "developed to be more efficient to fabricate, safer to construct, and more cost effective" when compared to the formerly used AASHTO and Florida Bulb-T girders[1]. Because FIB girders have relatively wide bottom flanges, they can accommodate more than double the number prestressing strands as comparable AASHTO sections of similar depth. The large quantities of prestressing allow the FIB girders to span lengths unobtainable with the AASHTO girders.

FIBs are similar to girders used in other states, including NU girders in Nebraska[2] and WF girders in Washington[3]. The FIB, NU, and WF girders each have bottom flanges that are wider and more slender than comparable AASHTO girders. Wide bottom flanges can house more prestressing strands and improve structural efficiency but can also be prone to splitting cracks that typically form during or immediately following prestress transfer (Figure 1).

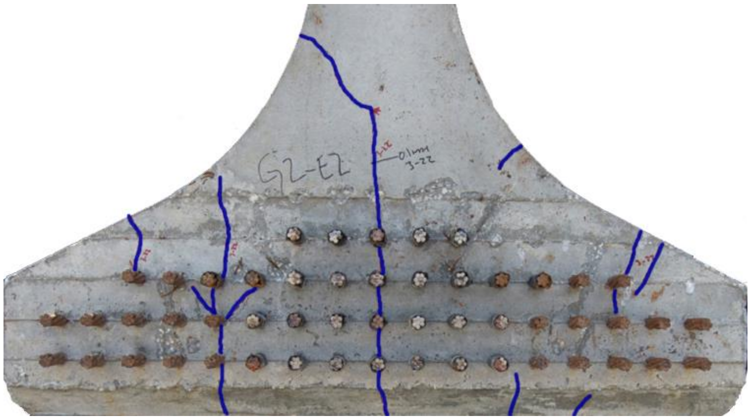
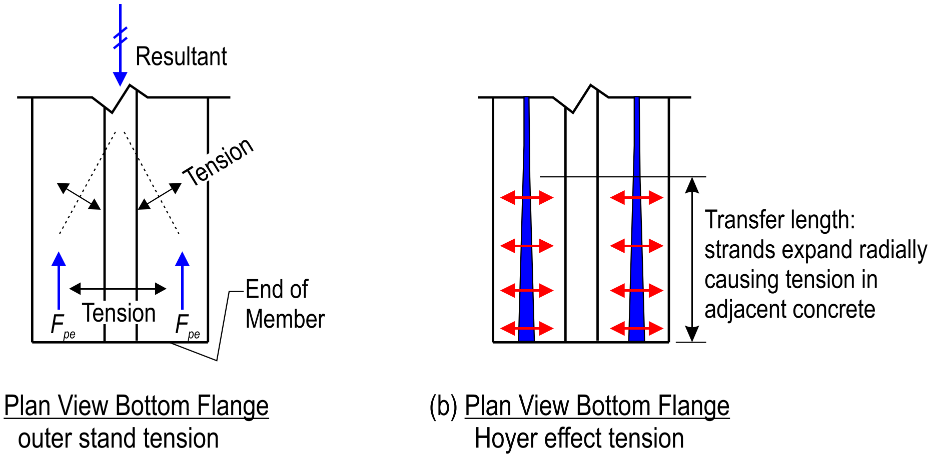


Figure 1–Flange splitting cracks (enhanced) in FIB girder.

Flange splitting cracks can negatively affect girder durability by allowing chlorides and other deleterious materials access to prestressing strands and mild reinforcement. Once in contact with steel the chlorides cause corrosion and can significantly reduce life span. Splitting cracks on the top surface of the bottom flange are particularly problematic because gravity will naturally pull water (and any dissolved chlorides) into the cracks. In addition to affecting durability, flange splitting cracks can also limit force transfer between strands and concrete, thereby reducing girder capacity and ductility[4-6].

Previous research has demonstrated that flange splitting cracks form as a consequence of concentrating fully bonded strands in the outer portion of the flange[6]. Such strand patterns lead to transverse tension in the bottom flange (Figure 2a). Tensile stresses also occur due to the Hoyer effect[7] (Figure 2b). Strands contract radially during pretensioning due to Poisson effect. During prestress transfer the strands within the transfer length expand towards their former diameter but are partially restrained by the surrounding concrete. This restraint of expansion creates tensile stresses in the concrete surrounding the strands. The superposition of tension stresses from eccentric prestressing force and Hoyer effect may lead to the formation of splitting cracks when these transverse stresses exceed concrete tensile capacity.



(a) Plan View Bottom Flange outer stand tension

(b) Plan View Bottom Flange Hoyer effect tension

Figure 2– (a) End tension due to outer strand eccentricity, (b) tension due to Hoyer effect.

This paper presents results of an experimental program conducted to evaluate different bottom flange details and their effects on flange splitting cracks. Variables in the program included: quantity and configuration of confinement reinforcement, presence/lack of steel bearing plates, prestressing strand layout, and partial debonding of up to 45% of prestressing strands. The following paragraphs discuss provisions from the 2010 AASHTO LRFD Bridge Design Specifications[8] (hereafter "LRFD") and from the 2013 FDOT Structural Design Guidelines[9] that are relevant to the test variables.

Article 5.10.10.2 of LRFD requires that confinement reinforcement be placed around prestressing strands in the bottom flange of I-girders over a distance 1.5*d* from girder ends. Confinement bars must be #3 or larger and must be spaced no more than 6 in. apart. While LRFD code and commentary do not discuss the purpose of confinement reinforcement, it is likely that one purpose is to control flange splitting cracks.

Strand shielding (partial debonding) is governed by article 5.11.4.3 of LRFD. This article limits shielding to no more than 25% of strands in a girder. Limits are also placed on the percentage of shielded strands in a given row (40%), and the quantity of shielded strands that can have shielding terminate at the same section (greater of 40% or four strands). Shielding is required to be symmetric about the cross-section centerline. In addition to LRFD requirements, the FDOT also prohibits shielding of adjacent strands. Research from Okumus and Oliva (2013) analytically demonstrated that partial shielding of prestressing strands at member ends can have significant effect on reducing flange splitting cracks[10].

FDOT requires that embedded steel bearing plates be placed at the end of all FIB girders. These plates are anchored to the bottom of the beam by headed studs welded to the plate.

Use of the plates was precipitated by research from Cook and Reponen[11]. They recommended that bearing plates be placed at girder ends to reduce friction between girders and stressing beds. This friction was found culpable in vertical cracks forming at the bottom corner of girders during prestress transfer. Bearing plates were included in the test program to evaluate the possibility that they also reduce the likelihood of flange splitting cracks.

SPECIMEN DETAILS AND FABRICATION

Three 50-ft. long FIB-54 girders were built according to the schedule of variables shown in Table 1. Each end of each girder was detailed differently, resulting in six unique specimens. Girders and specimens were labeled using the convention shown in Figure 3. Figure 3 also presents graphical descriptions of each specimen.

Table 1–FIB-54 test girder and specimen variables.

Girder	Specimen	Bearing plate	Strand bond pattern	Confinement reinforcement
W	WN	None	Web	Mod
	WB	Yes	Web	Mod
F	FN	None	Flange	Mod
	FB	Yes	Flange	Mod
D	DC	Yes	Design	FDOT
	DM	Yes	Design	Mod

FDOT: Detailed per FDOT design standards
Mod: Detailed with modifications to FDOT design standards
Web: Fully bonded strands placed below web (24 fully bonded strands)
Flange: Fully bonded strands placed in outer portion of flange (24 fully bonded strands)
Design: Strand pattern based on prototype design (45 fully bonded strands)

Essential specimen details are presented in Figure 4 and Figure 5, and tested material properties are listed in Table 2. A comprehensive discussion of details, construction procedures, materials properties, and construction events is presented by Ross et al.[12]. Test variables are discussed in the subsequent paragraphs.

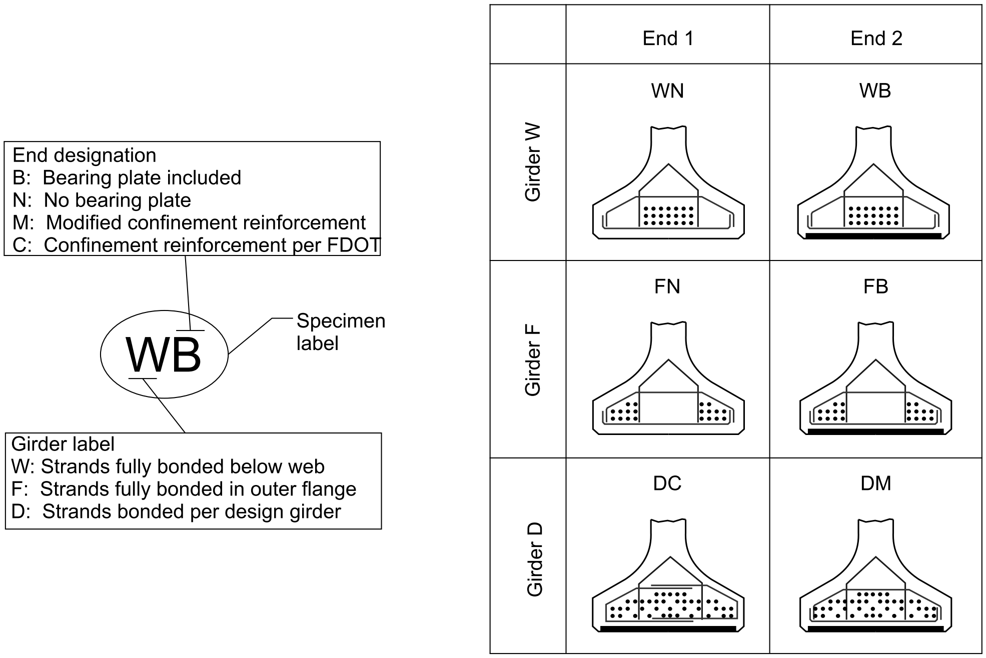


Figure 3–Labeling and graphical specimen descriptions.

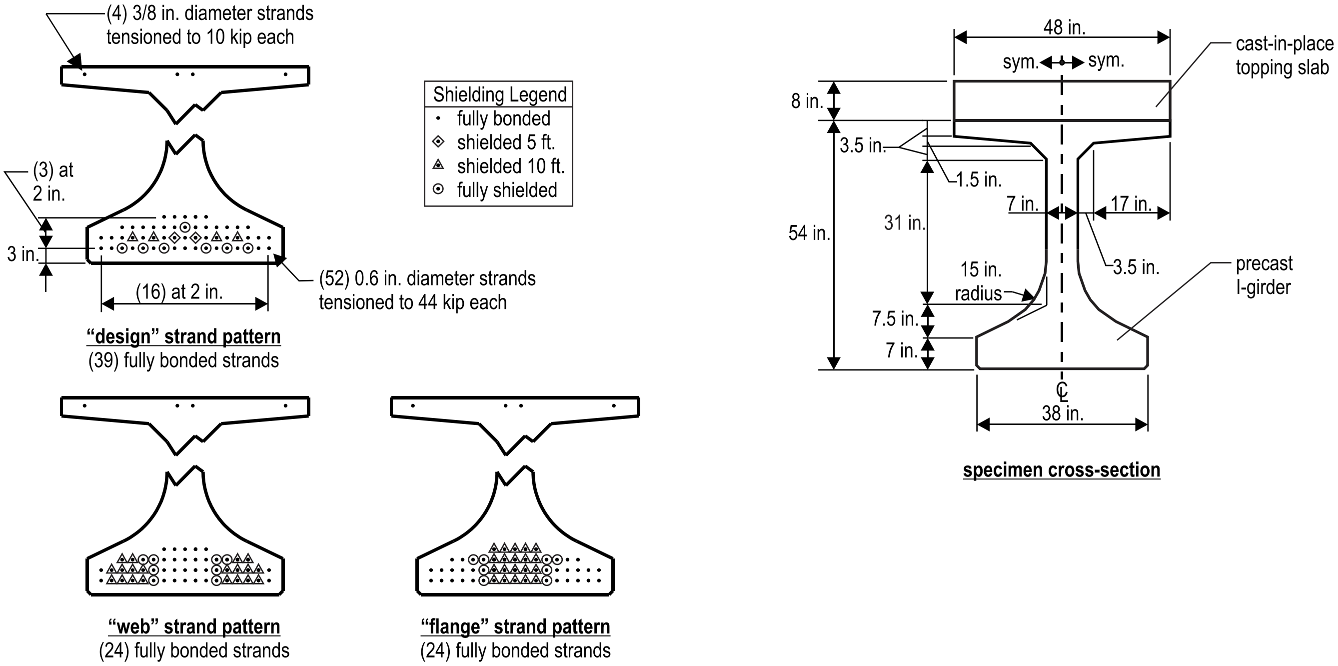


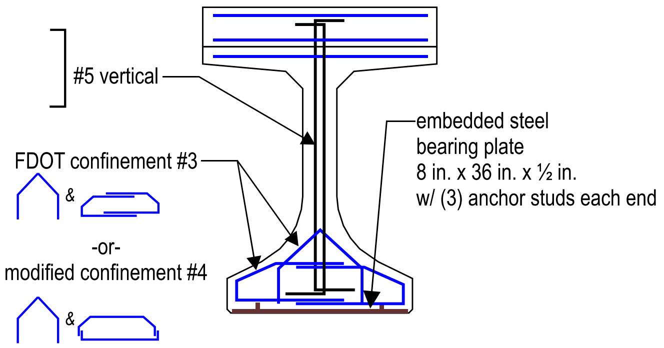
Figure 4–Prestressing and cross-section.

Bearing plates. Presence/lack of steel bearing plates was included as a variable to evaluate the effect of bearing plates on flange splitting cracks. Plates were anchored to the bottom of girders using headed studs.

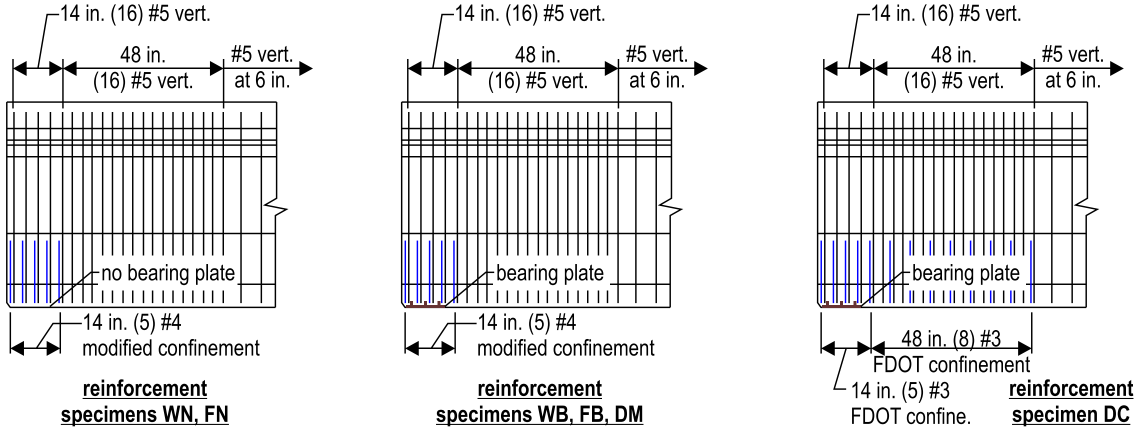
Strand bond pattern. Previous research has demonstrated that strand pattern can affect the occurrence of flange splitting cracks, and that patterns with fully bonded strands concentrated in the outer flange are particularly problematic[6]. Three different patterns were used in the test program. The “design” pattern was selected to match a pattern used on an actual girder design. The design pattern had (39) fully bonded strands. The “web” and “flange” patterns had (24) fully bonded strands and were designed to evaluate the effects of concentrating fully bonded strands below the web and in the outer flange. The “web” and “flange” patterns violated LRFD requirements for quantity and placement of strand shielding, but were useful for evaluating extreme conditions. Fully shielded strands were used in the “web” and “flange” patterns to allow each of the specimens to be constructed simultaneously on the same stressing bed.

Confinement reinforcement. LRFD standards require that #3 confinement reinforcement encompass prestressing strands for 1.5d from member ends. Building on previous research which demonstrated that forces in confinement reinforcement are greatest near member ends[13], a modified confinement detail was used in five of the six specimens. The modified detail utilized #4 bars and concentrated all confinement reinforcement within 16 in. (approximately 0.3d) of the member end. Specimen DC did not use the modified detail but had #3 bars spread over a greater distance from the end.

Girders were built by Standard Concrete Products of Tampa, FL according to the timeline in Figure 6. This figure also lists inspection and testing dates. Load tests are reported by Ross et al.[12]. Girders were constructed simultaneously in the same stressing bed and using the same materials. Concrete for the girders was a self-consolidating mix that was batched at the precast facility. Prestress force was transferred by flame cutting the strands (Figure 7) three days after casting. Strands in production girders fabricated at the plant are typically cut sooner than three days. The additional time before strand cutting was needed to install research instrumentation. Cuts were made simultaneously along individual strands at locations between girders and at the ends of the stressing bed. The cutting sequence was outside-in and top-to-bottom. Fabrication and quality control procedures were typical of FDOT projects. Figure 8 shows specimens DC and DM. Specimen DC had confinement reinforcement based on FDOT standards; specimen DM had modified confinement reinforcement.



reinforcement configuration



reinforcement specimens WN, FN

reinforcement specimens WB, FB, DM

reinforcement specimen DC

Figure 5–Mild reinforcement and bearing plates.

Table 2 - Material Properties.

Material	Property	Tested Value
Concrete (FDOT Class VI)	Prestress transfer compressive strength	7320 psi
	28-day compressive strength	8730 psi
	100-day compressive strength	10,520 psi
Prestressing strands (ASTM A416)	Stress at 1% elongation	260 ksi
	Ultimate stress	286 ksi
	NASP standard bond test	22.9 kip
#5 reinforcement (ASTM A615)	Yield stress	63 ksi
	Ultimate stress	104 ksi
#4 reinforcement (ASTM A615)	Yield stress	76 ksi
	Ultimate stress	107 ksi
#3 reinforcement (ASTM A615)	Yield stress	85 ksi
	Ultimate stress	115 ksi

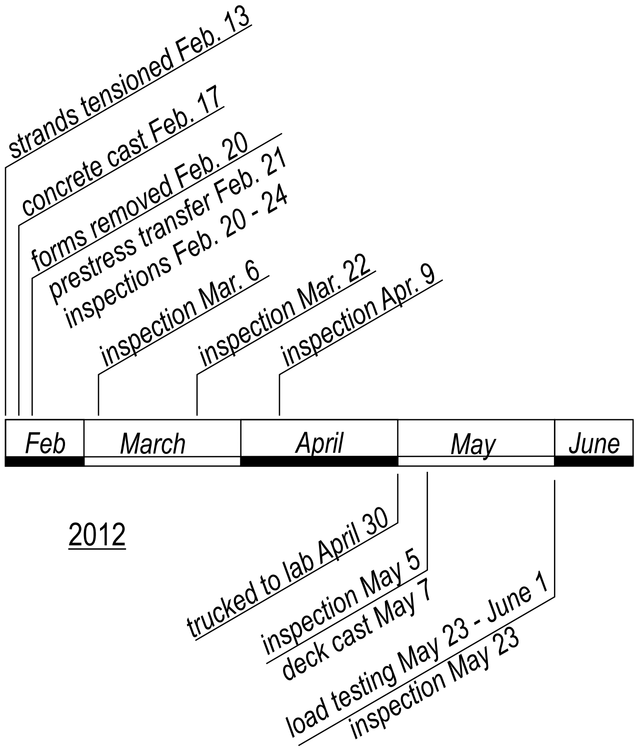


Figure 6 – Fabrication and inspection timeline.

Figure 7 – Prestress transfer by flame cutting strands. Specimens were built simultaneously on the same prestressing line.

Figure 8 - Reinforcement for specimen DC (left) and specimen DM (right). Specimen DM had more confinement reinforcement (by cross sectional area) near the end. Specimen DC had more confinement reinforcement overall.

DATA COLLECTION AND ANALYSIS METHODS

Strain and crack data were collected during and in the months following prestress transfer. Strain data are not discussed in this paper but are presented in Ross et al.[12]. Crack data were collected by visual inspection on the dates shown in Figure 6. Visual inspections included marking cracks with a crayon and documenting locations and lengths by tape measure and photograph. Crack widths were measured at one or two locations along each crack using a microscope that was precise to +/- 0.001 in.

Severity of flange cracking was quantified and compared using the metrics of total length and total area. Total length was calculated by the summing the length of all individual flange splitting cracks in a specimen. Total area was calculated as the summation of the areas of all individual flange splitting cracks.

Crack area was calculated by multiplying the length of an individual crack by its representative width. Representative widths were derived from width measurements taken by microscope. The means of determining representative width was different depending on crack location. For cracks on the end face of a specimen, the representative width was taken directly as the measured width. For cracks on the side or bottom of a specimen the representative width was taken as the average of all widths measured along the crack. For some cracks on the sides and bottom only a single measurement was taken. Single measurements were typically made near the specimen ends where cracks had their greatest widths. In these cases, the representative width was taken as one-half of the measured width.

RESULTS AND DISCUSSION

Three types of cracks were observed in the girder specimens:

- Top flange flexural cracks
- Web splitting cracks
- Flange splitting cracks

Web and flange cracks are shown in Figure 9. Flange splitting cracks are of primary interest in this paper and are discussed in the following paragraphs. Top flange flexural cracks and web splitting cracks are not discussed in this paper, but are addressed in the author's report for the FDOT[12].

Flange splitting cracks were first observed during prestress transfer. Cracks grew in width, length and in quantity in the days and weeks following prestress transfer. Figure 9 shows the web and flange cracks in each specimen three months after prestress transfer. Additional cracks were observed on the bottom of surface of each specimen. The bottom surfaces of the specimens were inspected after placement of the specimens on dunnage in the storage yard at the precast facility. The width, length, and location the bottom surface cracks were roughly equivalent to cracks observed on the top surface of the bottom flange.

Locations of cracks shown in Figure 9 can be understood by considering the strand bond pattern associated with the test specimens. For example, specimens WN and WB had flange splitting cracks located 10ft from their ends. These cracks formed within the transfer length of the partially shielded strands and were likely due to the fact that nearly all of the strands in the outer portion of the flange were debonded up to this point (Figure 4). Cracks then formed due to transverse tensile stresses and Hoyer stresses from the transfer of a large prestress force over a relatively short distance.

Significant bottom flange cracking occurred at the ends of specimens FB and FN, both of which had fully bonded strands in the outer flange and partially shielded strands below the web. Cracks at the end of specimens FB and FN are attributed to transverse tension at the member end that formed due to the fully bonded strands in the outer flange (Figure 2a). Flange cracks at the ends of FN and FB intersected strands suggesting that the Hoyer effect also contributed to the tensile stresses and crack formation.

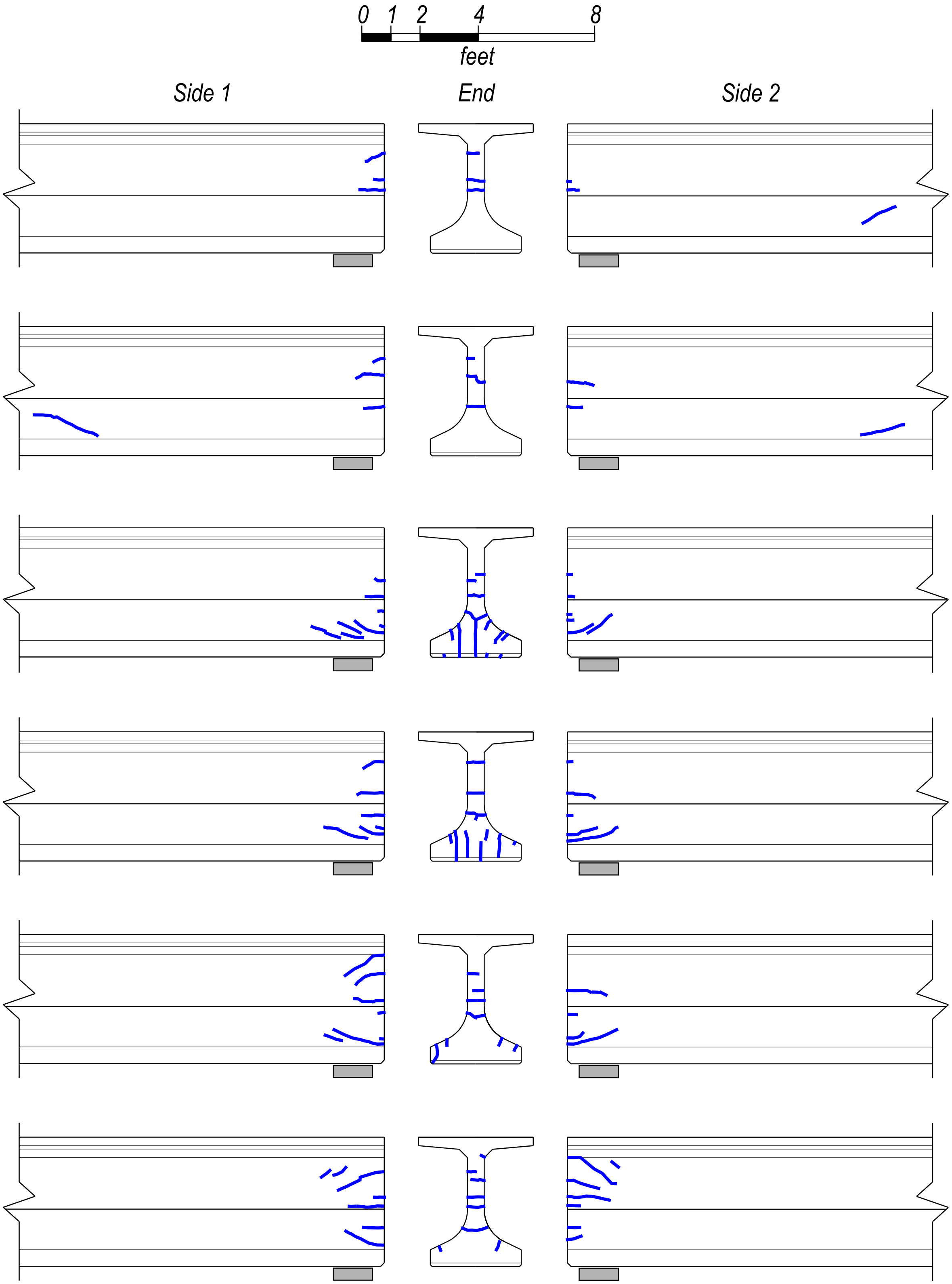


Figure 9 – Web and flange splitting cracks. Flexural cracks in the top flange are not shown.

Specimens WB, WN, FB and FN all intentionally exceeded the AASHTO limits of total percentage of shielded strands and quantity of strand shielding that terminate at a given section. Termination of shielding resulted in splitting cracks 10 ft. from the end of WB and WN, but not in FB and FB. The absence of cracking at the termination of strand shielding in FN and FB is attributed to placement of the shielded strands. Partially shielded strands in specimens FN and FB were located below the web and had sufficient cover distance and confinement to prevent cracking.

Length and area of the bottom flange cracks are quantified in Figure 10. Cracking was most severe in specimen FN, having 105% greater length and 115% greater area than the averages of all specimens. Severity of cracking in FN is attributed to the "flange" strand bond pattern (Figure 4) which placed fully bonded strands in the outer flange. Absence of a bearing plate is also believed to have had negative affect on cracking in specimen FN.

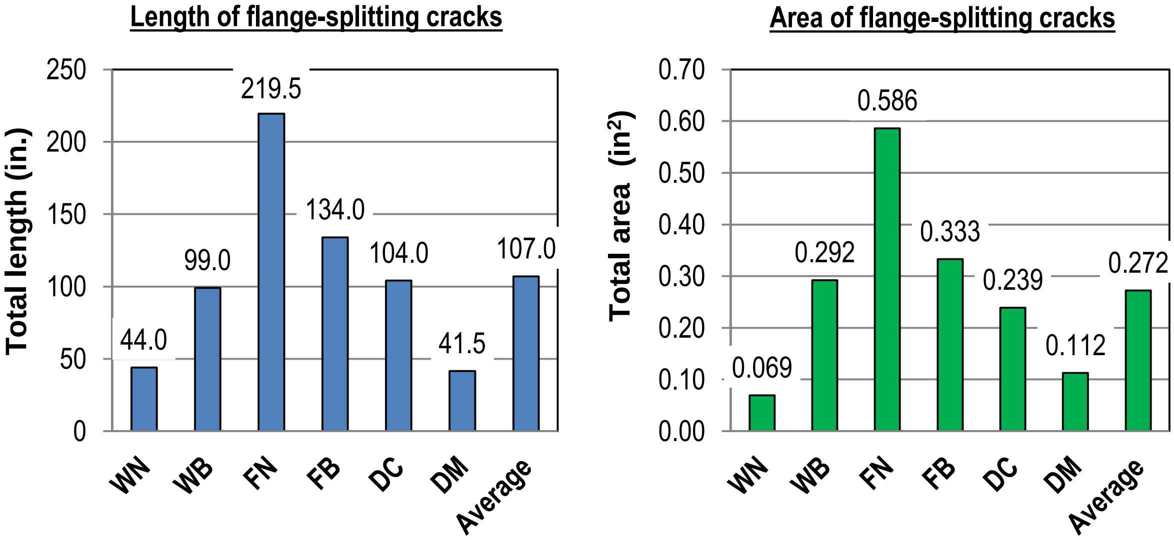


Figure 10–Flange splitting cracks.

Specimen FB had the second greatest degree of flange splitting cracks. FB had an embedded steel bearing plate and utilized the "flange" strand bond pattern (Figure 4). Specimen FB had 40% less cracking by length and 43% less cracking by area than FN. Reduced cracking in FB, relative to FN, is attributed to the confining effect of the bearing plate.

Comparison of cracks between WN and WB is may seem counter-intuitive because specimen WB had a bearing plate yet had more than twice the cracking length than that of WN. Flange cracks in these specimens occurred away from the member ends where shielding terminated. Because splitting cracks were located away from the bearing plate at the member end, it is reasonable to assume that the bearing plate did not affect cracking these specimens.

Specimens DC and DM utilized the "design" strand bond pattern, which included (39) fully bonded strands distributed throughout the bottom flange (Figure 4). The other specimens had only (24) fully bonded strands. Although DC and DM had the largest quantity of fully bonded strands, they did not have the greatest degree of cracking. This observation indicates that placement of bonded and shielded strands has greater effect on flange cracking than does quantity of fully bonded strands.

A crack intersected the outermost strand in the third row in each of the specimens. The strand at this location had only 2.5 in. of clear cover, the least amount of cover of any strand in the test specimens. In specimens WN and WB cracks at this strand occurred 10ft away from the end where shielding for the strand terminated. In all other specimens the crack formed at the member end (Figure 11). It is recommended that this location be avoided when designing strand patterns in FIB girders.

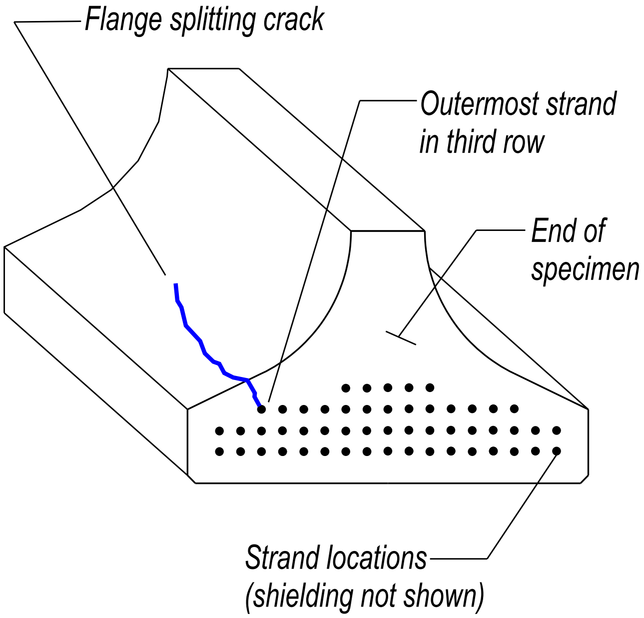


Figure 11–Flange splitting crack at outermost strand.

The longest flange cracks in the test program were approximately 30 in. in length. Transfer length calculated using LRFD provisions was 36 in. for the test specimens. Based on this comparison LRFD transfer length was comparable to the observed flange crack lengths and may be a reasonable guideline for placement of confinement reinforcement to control flange cracking. Correlation between flange splitting crack length and transfer length is attributed to the aggregate tensile stresses from the Hoyer effect and eccentricity of the strands in the outer flange (Figure 2).

Effects of confinement configuration can be compared using results from specimens DC and DM. Specimen DC had #3 confinement reinforcement distributed over 64 in. from the end. DM had #4 confinement reinforcement but had fewer total confinement bars than DC. All of the confinement reinforcement in DC was placed within 16 in. of the member end. Specimen DC had 2.5 times more flange cracking by length and 2.1 times more flange cracking by area than did specimen DM. Thus the modified confinement reinforcement performed better at controlling flange splitting cracks than did the FDOT configuration. This is attributed to the fact that specimen DM had a greater area of reinforcement placed closer to the end. Although the modified reinforcement scheme was more effective in controlling flange cracks it did not perform as well as the FDOT scheme in load tests[12]. Specimen DM with modified confinement had 7% less shear capacity in load tests than did DC.

SUMMARY AND CONCLUSIONS

Six FIB-54 test specimens were fabricated and monitored to evaluate the effects of various end region details on bottom flange splitting cracks. Variables in the test program included: quantity/configuration of confinement reinforcement, presence/lack of steel bearing plates, prestressing strand quantity and layout, and partial debonding of up to 45% of prestressing strands. Formation and growth of flange splitting cracks were monitored for 3 months after prestress transfer. Salient conclusions and observations are listed below:

- Placement of fully bonded strands had the greatest effect on flange splitting cracks of any variable in the test program. Specimens with fully bonded strands concentrated in the outer portions of the bottom flange (FN and FB) had 2.1 times more flange cracking (by length) than the average of all specimens.
- Embedded steel bearing plates with shear studs improved control of flange splitting cracks. Specimen FB with a bearing plate had 40% less flange cracking (by length) than did the comparable specimen, FN, without a plate.
- The AASHTO LRFD limitations for termination of strand shielding at a given section were effective in preventing splitting cracks away from the member end. Specimens DC and DM complied with the LRFD requirements and did not have splitting cracks within the transfer length of shielded strands.
- Increased area of confinement reinforcement close to the member end (specimen DM) provided better control of flange splitting cracks. Specimen DM utilized #4 confinement concentrated at the end and had 60% less flange cracks (by length) than with specimen DC, which had #3 bars distributed through the end region. This conclusion is tempered by the observation that the specimen DM did not perform as well in load testing[12].
- To impede flange splitting cracks, strands should be placed as close to the section centerline and with as much clear cover as possible.

FUTURE CONSIDERATIONS

Specimens in the test program had strand shielding patterns based on actual girders (DM and DC) and based on the extremes of possible strand shielding patterns (WN, WB, FN, and FB). The authors recommend that any follow-up research include evaluation of shielding patterns that are somewhere between the extremities tested in the current program.

The strand shielding pattern shown in Figure 12 combines the beneficial aspects of the ‘web’ and ‘design’ strand patterns. Similar to the ‘web’ pattern, fully bonded strands in Figure 12 are placed concentrically in the bottom flange, and thus will not lead to end tension associated with eccentric outer strands (Figure 2a). Cover distance over of the fully bonded strands will provide confinement and assist in controlling cracking due the Hoyer effect (Figure 2b). Similar to the ‘design’ pattern, termination locations of strand shielding are staggered, and the likelihood of flange cracks at the termination locations will be small. In addition to reducing the likelihood of flange cracking, it is also believed that the pattern in Figure 12 has advantages from a strength perspective. For example, the fully bonded strands below the web can act as longitudinal tie reinforcement without contributing to lateral-splitting failure and any associated reduction in capacity[13].

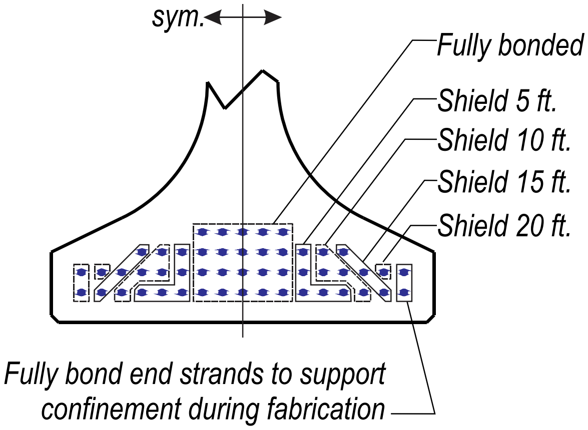


Figure 12–Recommended strand shielding pattern for future research

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