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5 **EXPERIMENTAL EVALUATION OF BOTTOM FLANGE SPLITTING CRACKS**
6 **IN I-GIRDERS**
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12
13 **ABSTRACT**
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15 *To improve the structural efficiency of prestressed concrete highway bridges many state*
16 *transportation departments, including the Florida Department of Transportation, have*
17 *introduced new I-girder sections. These sections have relatively wide bottom flanges*
18 *capable of accommodating more than double the number prestressing strands as comparable*
19 *AASHTO sections of similar depth. The large quantities of prestressing allow the new*
20 *girders to span lengths unobtainable with the AASHTO sections. One concern with the new*
21 *girders, however, is the propensity for splitting cracks to form in the bottom flange at girder*
22 *ends during prestress transfer. To evaluate this concern, six 54-in. deep Florida I-Beam*
23 *(FIB) specimens were fabricated and monitored during prestress transfer and during the*
24 *following months. Variables in the test specimens included: quantity/configuration of*
25 *confinement reinforcement, presence/lack of steel bearing plates, prestressing strand layout,*
26 *and partial debonding of up to 45% of prestressing strands. Bottom flange cracks were*
27 *monitored, recorded, and quantified to determine the effects of test variables. Detailing and*
28 *design recommendations were made based on the results of the test program.*
29 *Recommendations will be of interest to engineers and fabricators who work with I-girders*
30 *having wide and/or heavily prestressed bottom flanges.*
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34 **Keywords:** Pretensioned Girders, Confinement Reinforcement, Bearing Plates, Strand
35 Debonding, Flange Splitting, End Region
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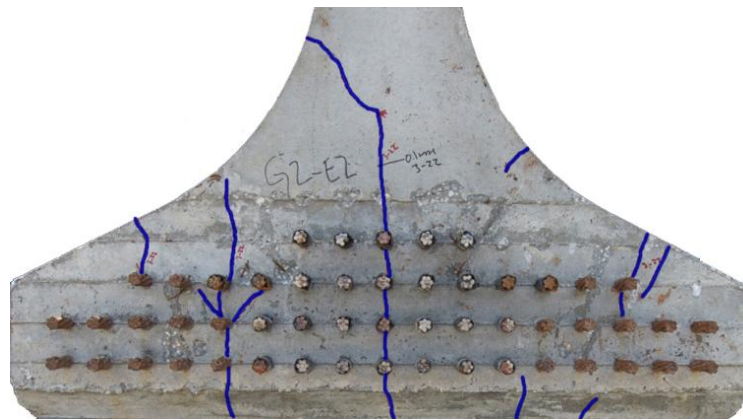
37 **INTRODUCTION**

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39 In 2009 the Florida Department of Transportation (FDOT) introduced the Florida I-Beam
40 (FIB) series as their standard for prestressed concrete bridges. The FIB girders were
41 “developed to be more efficient to fabricate, safer to construct, and more cost effective”
42 when compared to the formerly used AASHTO and Florida Bulb-T girders¹. Because FIB
43 girders have relatively wide bottom flanges, they can accommodate more than double the
44 number prestressing strands as comparable AASHTO sections of similar depth. The large
45 quantities of prestressing allow the FIB girders to span lengths unobtainable with the
46 AASHTO girders.

47

48 FIBs are similar to girders used in other states, including NU girders in Nebraska² and WF
49 girders in Washington³. The FIB, NU, and WF girders each have bottom flanges that are
50 wider and more slender than comparable AASHTO girders. Wide bottom flanges can house
51 more prestressing strands and improve structural efficiency but can also be prone to splitting
52 cracks that typically form during or immediately following prestress transfer (Figure 1).
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Figure 1–Flange splitting cracks (enhanced) in FIB girder.

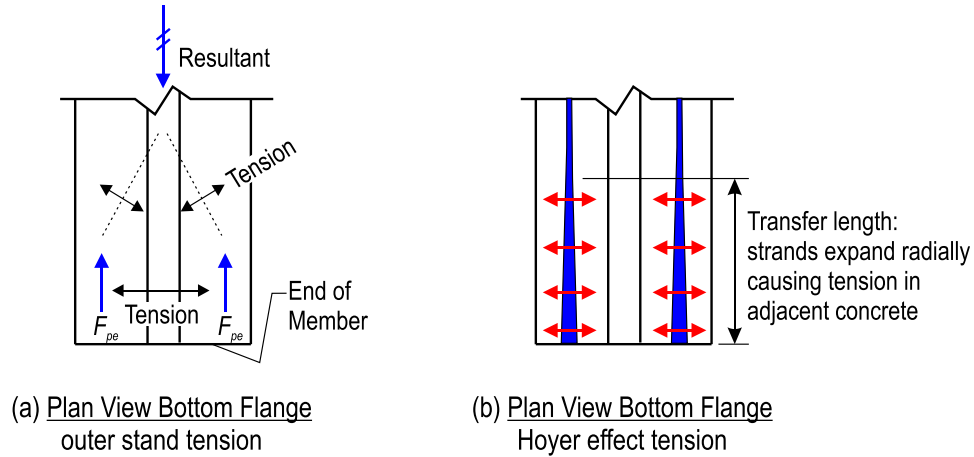
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57 Flange splitting cracks can negatively affect girder durability by allowing chlorides and other
58 deleterious materials access to prestressing strands and mild reinforcement. Once in contact
59 with steel the chlorides cause corrosion and can significantly reduce life span. Splitting
60 cracks on the top surface of the bottom flange are particularly problematic because gravity
61 will naturally pull water (and any dissolved chlorides) into the cracks. In addition to
62 affecting durability, flange splitting cracks can also limit force transfer between strands and
63 concrete, thereby reducing girder capacity and ductility⁴⁻⁶.

64

65 Previous research has demonstrated that flange splitting cracks form as a consequence of
66 concentrating fully bonded strands in the outer portion of the flange⁶. Such strand patterns
67 lead to transverse tension in the bottom flange (Figure 2a). Tensile stresses also occur due to
68 the Hoyer effect⁷ (Figure 2b). Strands contract radially during pretensioning due to Poisson
69 effect. During prestress transfer the strands within the transfer length expand towards their
70 former diameter but are partially restrained by the surrounding concrete. This restraint of

71 expansion creates tensile stresses in the concrete surrounding the strands. The superposition
 72 of tension stresses from eccentric prestressing force and Hoyer effect may lead to the
 73 formation of splitting cracks when these transverse stresses exceed concrete tensile capacity.
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76
 77 Figure 2– (a) End tension due to outer strand eccentricity, (b) tension due to Hoyer effect.
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79 This paper presents results of an experimental program conducted to evaluate different
 80 bottom flange details and their effects on flange splitting cracks. Variables in the program
 81 included: quantity and configuration of confinement reinforcement, presence/lack of steel
 82 bearing plates, prestressing strand layout, and partial debonding of up to 45% of prestressing
 83 strands. The following paragraphs discuss provisions from the 2010 AASHTO LRFD Bridge
 84 Design Specifications⁸ (hereafter “LRFD”) and from the 2013 FDOT Structural Design
 85 Guidelines⁹ that are relevant to the test variables.
 86

87 Article 5.10.10.2 of LRFD requires that confinement reinforcement be placed around
 88 prestressing strands in the bottom flange of I-girders over a distance $1.5d$ from girder ends.
 89 Confinement bars must be #3 or larger and must be spaced no more than 6 in. apart. While
 90 LRFD code and commentary do not discuss the purpose of confinement reinforcement, it is
 91 likely that one purpose is to control flange splitting cracks.
 92

93 Strand shielding (partial debonding) is governed by article 5.11.4.3 of LRFD. This article
 94 limits shielding to no more than 25% of strands in a girder. Limits are also placed on the
 95 percentage of shielded strands in a given row (40%), and the quantity of shielded strands that
 96 can have shielding terminate at the same section (greater of 40% or four strands). Shielding
 97 is required to be symmetric about the cross-section centerline. In addition to LRFD
 98 requirements, the FDOT also prohibits shielding of adjacent strands. Research from Okumus
 99 and Oliva (2013) analytically demonstrated that partial shielding of prestressing strands at
 100 member ends can have significant effect on reducing flange splitting cracks¹⁰.
 101

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

104 Use of the plates was precipitated by research from Cook and Reponen¹¹. They
 105 recommended that bearing plates be placed at girder ends to reduce friction between girders
 106 and stressing beds. This friction was found culpable in vertical cracks forming at the bottom
 107 corner of girders during prestress transfer. Bearing plates were included in the test program
 108 to evaluate the possibility that they also reduce the likelihood of flange splitting cracks.

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110 **SPECIMEN DETAILS AND FABRICATION**

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

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

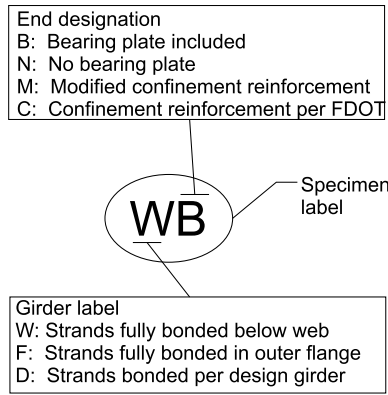
Girder	Specimen	Bearing plate	Strand bond pattern	Confinement reinforcement
W	WN	None	Web	Mod
	WB	Yes	Web	Mod
F	FN	None	Flange	Mod
	FB	Yes	Flange	Mod
D	DC	Yes	Design	FDOT
	DM	Yes	Design	Mod

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)

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

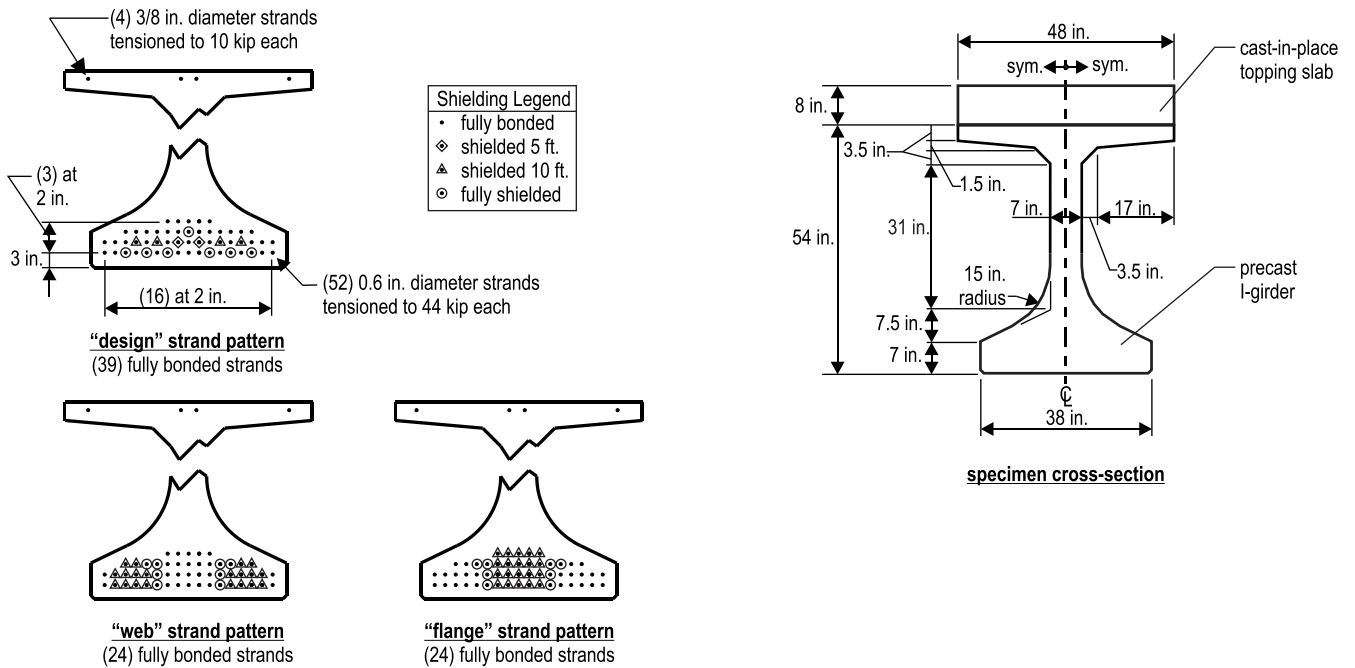
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	End 1	End 2
Girder W	WN 	WB
Girder F	FN 	FB
Girder D	DC 	DM

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Figure 3—Labeling and graphical specimen descriptions.



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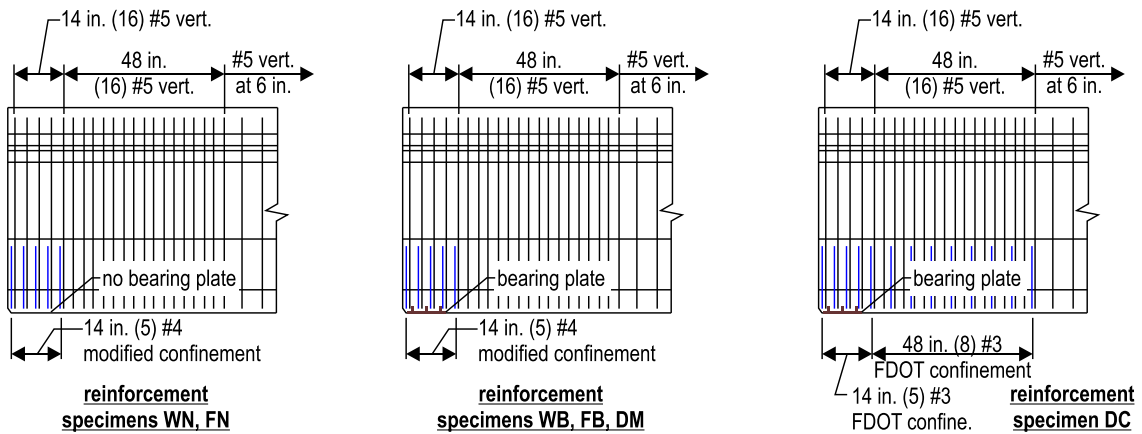
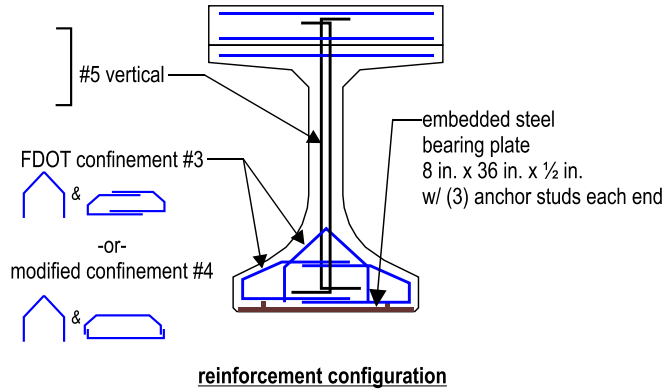
Figure 4—Prestressing and cross-section.

133 **Bearing plates.** Presence/lack of steel bearing plates was included as a variable to evaluate
134 the effect of bearing plates on flange splitting cracks. Plates were anchored to the bottom of
135 girders using headed studs.
136

137 **Strand bond pattern.** Previous research has demonstrated that strand pattern can affect the
138 occurrence of flange splitting cracks, and that patterns with fully bonded strands concentrated
139 in the outer flange are particularly problematic⁶. Three different patterns were used in the
140 test program. The “design” pattern was selected to match a pattern used on an actual girder
141 design. The design pattern had (39) fully bonded strands. The “web” and “flange” patterns
142 had (24) fully bonded strands and were designed to evaluate the effects of concentrating fully
143 bonded strands below the web and in the outer flange. The “web” and “flange” patterns
144 violated LRFD requirements for quantity and placement of strand shielding, but were useful
145 for evaluating extreme conditions. Fully shielded strands were used in the “web” and
146 “flange” patterns to allow each of the specimens to be constructed simultaneously on the
147 same stressing bed.
148

149 **Confinement reinforcement.** LRFD standards require that #3 confinement reinforcement
150 encompass prestressing strands for $1.5d$ from member ends. Building on previous research
151 which demonstrated that forces in confinement reinforcement are greatest near member
152 ends¹³, a modified confinement detail was used in five of the six specimens. The modified
153 detail utilized #4 bars and concentrated all confinement reinforcement within 16 in.
154 (approximately $0.3d$) of the member end. Specimen DC did not use the modified detail but
155 had #3 bars spread over a greater distance from the end.
156

157 Girders were built by Standard Concrete Products of Tampa, FL according to the timeline in
158 Figure 6. This figure also lists inspection and testing dates. Load tests are reported by Ross
159 et al.¹². Girders were constructed simultaneously in the same stressing bed and using the
160 same materials. Concrete for the girders was a self-consolidating mix that was batched at the
161 precast facility. Prestress force was transferred by flame cutting the strands (Figure 7) three
162 days after casting. Strands in production girders fabricated at the plant are typically cut
163 sooner than three days. The additional time before strand cutting was needed to install
164 research instrumentation. Cuts were made simultaneously along individual strands at
165 locations between girders and at the ends of the stressing bed. The cutting sequence was
166 outside-in and top-to-bottom. Fabrication and quality control procedures were typical of
167 FDOT projects. Figure 8 shows specimens DC and DM. Specimen DC had confinement
168 reinforcement based on FDOT standards; specimen DM had modified confinement
169 reinforcement.
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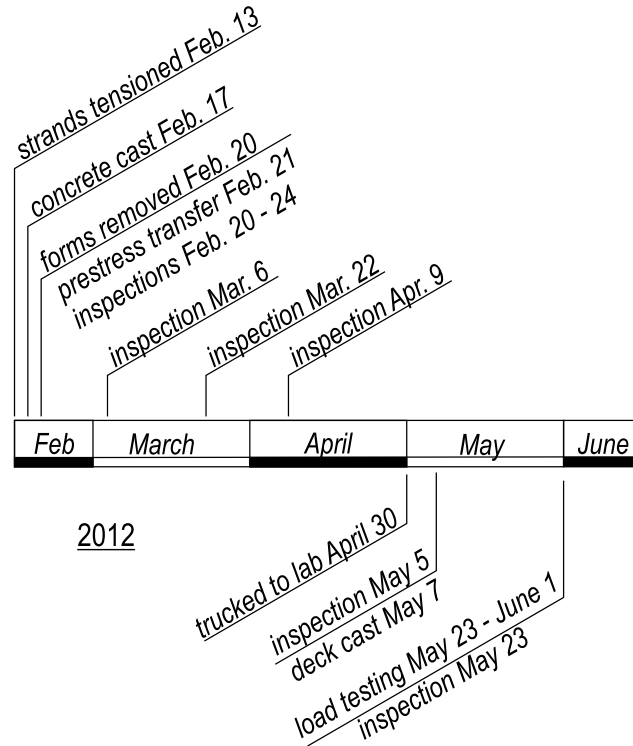
Figure 5—Mild reinforcement and bearing plates.

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

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Figure 6 – Fabrication and inspection timeline.



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



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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.

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DATA COLLECTION AND ANALYSIS METHODS

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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.

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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.

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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.

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222 RESULTS AND DISCUSSION

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224 Three types of cracks were observed in the girder specimens:

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- Top flange flexural cracks

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- Web splitting cracks

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- Flange splitting cracks

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229 Web and flange cracks are shown in Figure 9. Flange splitting cracks are of primary interest
230 in this paper and are discussed in the following paragraphs. Top flange flexural cracks and
231 web splitting cracks are not discussed in this paper, but are addressed in the author's report
232 for the FDOT¹².

232

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

240

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

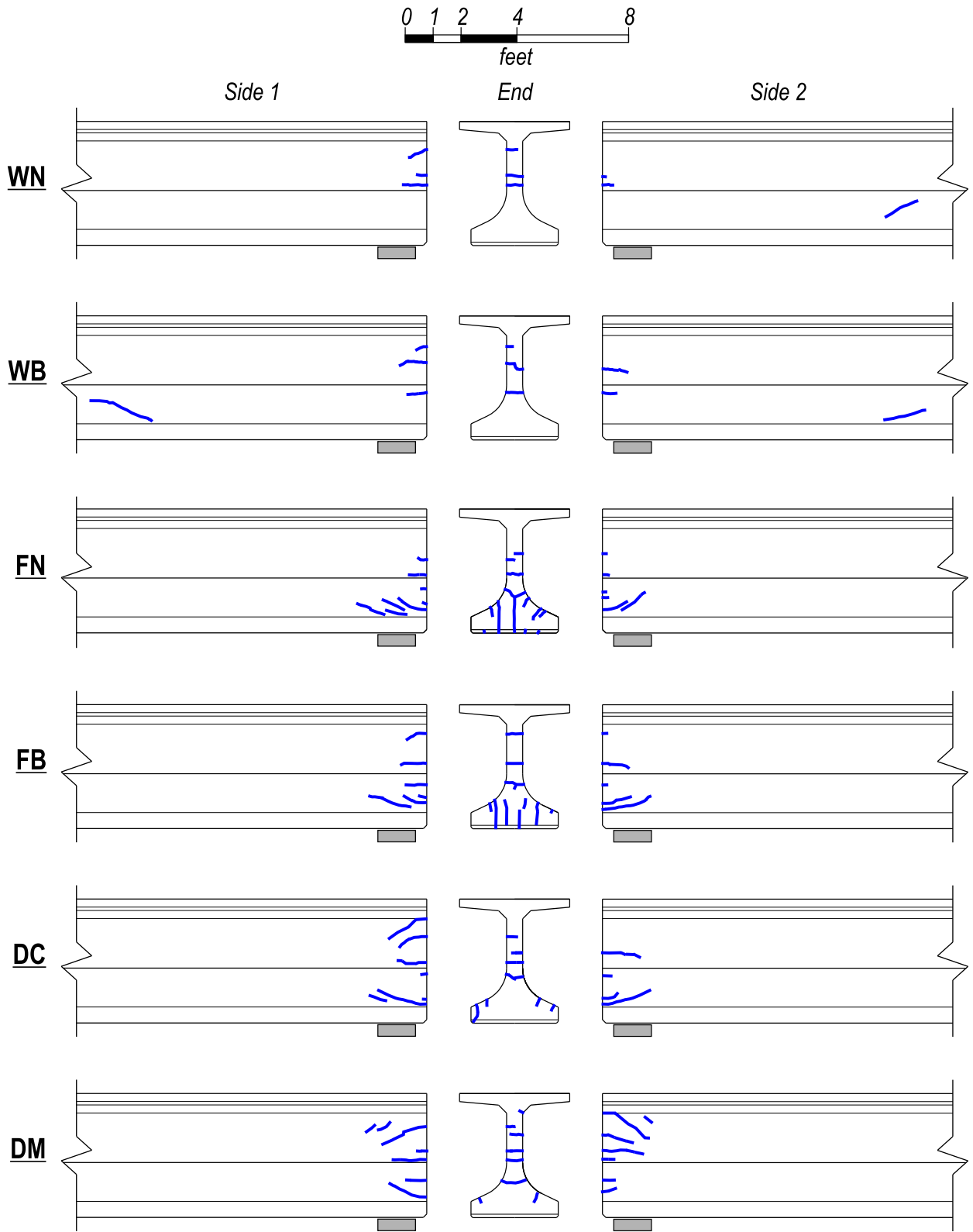
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249 Significant bottom flange cracking occurred at the ends of specimens FB and FN, both of
250 which had fully bonded strands in the outer flange and partially shielded strands below the
251 web. Cracks at the end of specimens FB and FN are attributed to transverse tension at the
252 member end that formed due to the fully bonded strands in the outer flange (Figure 2a).

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254 Flange cracks at the ends of FN and FB intersected strands suggesting that the Hoyer effect
255 also contributed to the tensile stresses and crack formation.

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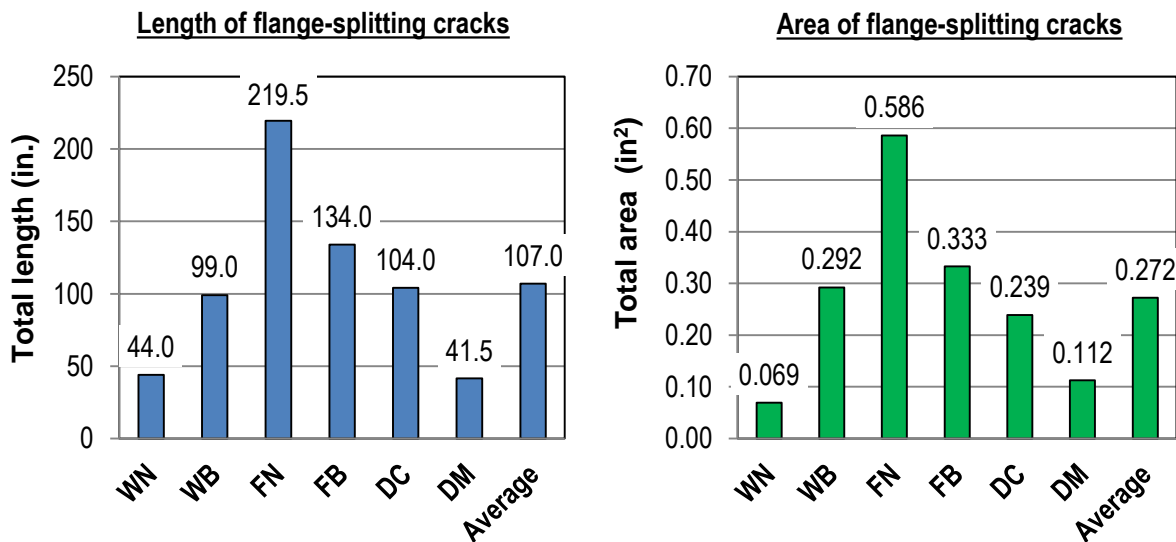


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Figure 9 – Web and flange splitting cracks. Flexural cracks in the top flange are not shown.

259 Specimens WB, WN, FB and FN all intentionally exceeded the AASHTO limits of total
 260 percentage of shielded strands and quantity of strand shielding that terminate at a given
 261 section. Termination of shielding resulted in splitting cracks 10 ft. from the end of WB and
 262 WN, but not in FB and FB. The absence of cracking at the termination of strand shielding in
 263 FN and FB is attributed to placement of the shielded strands. Partially shielded strands in
 264 specimens FN and FB were located below the web and had sufficient cover distance and
 265 confinement to prevent cracking.
 266

267 Length and area of the bottom flange cracks are quantified in Figure 10. Cracking was most
 268 severe in specimen FN, having 105% greater length and 115% greater area than the averages
 269 of all specimens. Severity of cracking in FN is attributed to the “flange” strand bond pattern
 270 (Figure 4) which placed fully bonded strands in the outer flange. Absence of a bearing plate
 271 is also believed to have had negative affect on cracking in specimen FN.
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274
 275 Figure 10–Flange splitting cracks.
 276

277 Specimen FB had the second greatest degree of flange splitting cracks. FB had an embedded
 278 steel bearing plate and utilized the “flange” strand bond pattern (Figure 4). Specimen FB had
 279 40% less cracking by length and 43% less cracking by area than FN. Reduced cracking in
 280 FB, relative to FN, is attributed to the confining effect of the bearing plate.
 281

282 Comparison of cracks between WN and WB is may seem counter-intuitive because specimen
 283 WB had a bearing plate yet had more than twice the cracking length than that of WN. Flange
 284 cracks in these specimens occurred away from the member ends where shielding terminated.
 285 Because splitting cracks were located away from the bearing plate at the member end, it is
 286 reasonable to assume that the bearing plate did not affect cracking these specimens.
 287

288 Specimens DC and DM utilized the “design” strand bond pattern, which included (39) fully
 289 bonded strands distributed throughout the bottom flange (Figure 4). The other specimens had

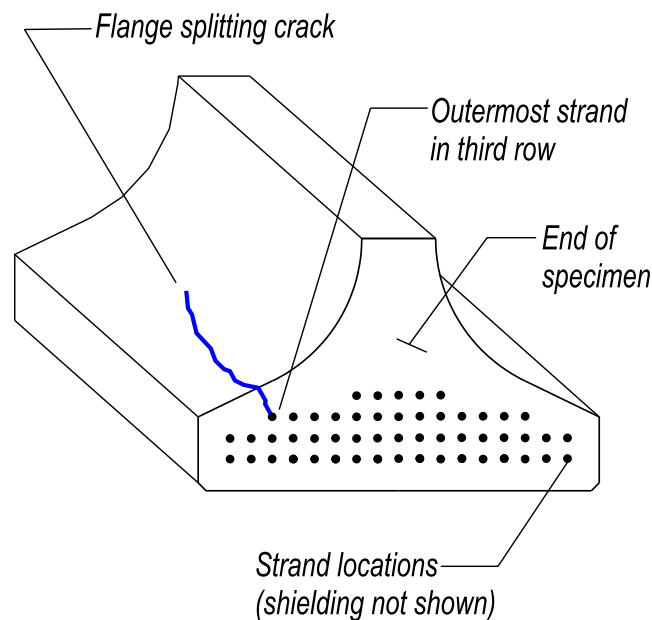
290 only (24) fully bonded strands. Although DC and DM had the largest quantity of fully
 291 bonded strands, they did not have the greatest degree of cracking. This observation indicates
 292 that placement of bonded and shielded strands has greater effect on flange cracking than does
 293 quantity of fully bonded strands.

294

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

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Figure 11—Flange splitting crack at outermost strand.

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

315

316 Effects of confinement configuration can be compared using results from specimens DC and
 317 DM. Specimen DC had #3 confinement reinforcement distributed over 64 in. from the end.
 318 DM had #4 confinement reinforcement but had fewer total confinement bars than DC. All

319 of the confinement reinforcement in DC was placed within 16 in. of the member end.
320 Specimen DC had 2.5 times more flange cracking by length and 2.1 times more flange
321 cracking by area than did specimen DM. Thus the modified confinement reinforcement
322 performed better at controlling flange splitting cracks than did the FDOT configuration. This
323 is attributed to the fact that specimen DM had a greater area of reinforcement placed closer to
324 the end. Although the modified reinforcement scheme was more effective in controlling
325 flange cracks it did not perform as well as the FDOT scheme in load tests¹². Specimen DM
326 with modified confinement had 7% less shear capacity in load tests than did DC.

327 **SUMMARY AND CONCLUSIONS**

328

329 Six FIB-54 test specimens were fabricated and monitored to evaluate the effects of various
330 end region details on bottom flange splitting cracks. Variables in the test program included:
331 quantity/configuration of confinement reinforcement, presence/lack of steel bearing plates,
332 prestressing strand quantity and layout, and partial debonding of up to 45% of prestressing
333 strands. Formation and growth of flange splitting cracks were monitored for 3 months after
334 prestress transfer. Salient conclusions and observations are listed below:
335

- 336 • Placement of fully bonded strands had the greatest effect on flange splitting cracks of
337 any variable in the test program. Specimens with fully bonded strands concentrated in
338 the outer portions of the bottom flange (FN and FB) had 2.1 times more flange
339 cracking (by length) than the average of all specimens.
- 340 • Embedded steel bearing plates with shear studs improved control of flange splitting
341 cracks. Specimen FB with a bearing plate had 40% less flange cracking (by length)
342 than did the comparable specimen, FN, without a plate.
- 343 • The AASHTO LRFD limitations for termination of strand shielding at a given section
344 were effective in preventing splitting cracks away from the member end. Specimens
345 DC and DM complied with the LRFD requirements and did not have splitting cracks
346 within the transfer length of shielded strands.
- 347 • Increased area of confinement reinforcement close to the member end (specimen
348 DM) provided better control of flange splitting cracks. Specimen DM utilized #4
349 confinement concentrated at the end and had 60% less flange cracks (by length) than
350 with specimen DC, which had #3 bars distributed through the end region. This
351 conclusion is tempered by the observation that the specimen DM did not perform as
352 well in load testing¹².
- 353 • To impede flange splitting cracks, strands should be placed as close to the section
354 centerline and with as much clear cover as possible.

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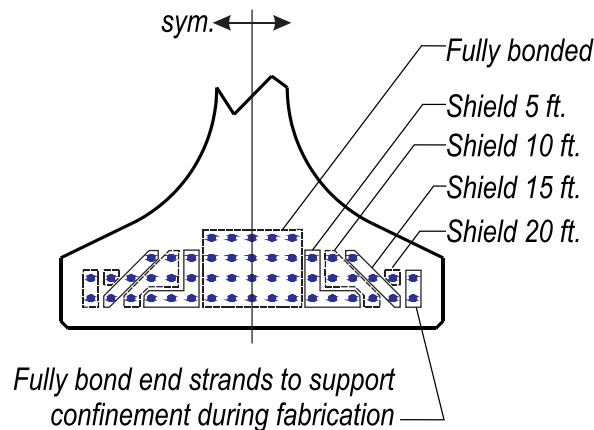
357 **FUTURE CONSIDERATIONS**

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

363 The strand shielding pattern shown in Figure 12 combines the beneficial aspects of the ‘web’
 364 and ‘design’ strand patterns. Similar to the ‘web’ pattern, fully bonded strands in Figure 12
 365 are placed concentrically in the bottom flange, and thus will not lead to end tension
 366 associated with eccentric outer strands (Figure 2a). Cover distance over of the fully bonded
 367 strands will provide confinement and assist in controlling cracking due the Hoyer effect
 368 (Figure 2b). Similar to the ‘design’ pattern, termination locations of strand shielding are
 369 staggered, and the likelihood of flange cracks at the termination locations will be small. In
 370 addition to reducing the likelihood of flange cracking, it is also believed that the pattern in
 371 Figure 12 has advantages from a strength perspective. For example, the fully bonded strands
 372 below the web can act as longitudinal tie reinforcement without contributing to lateral-
 373 splitting failure and any associated reduction in capacity¹³.

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Figure 12–Recommended strand shielding pattern for future research

378

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380

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 385 Pavlov of the FDOT Structures Design office assisted in design of the test girders. Girders
 386 were constructed by Standard Concrete Products in Tampa, FL.

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