DESIGN COMPARISON OF PRESTRESSED VS. POST-TENSIONED PRECAST CONCRETE BRIDGE BEAMS

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ABSTRACT

This paper explores the status and techniques of post-tensioning and precast concrete I-beams in bridge applications. Representative projects are presented to demonstrate the application and success of post-tensioning. To demonstrate the benefits of using post-tensioning to extend spans, multiple analysis of simple span post-tensioned I-beams were performed varying such characteristics as beam spacing, beam sections, beam depth and concrete strength. Tables were then developed to compare the maximum span length of a prestressed I-beam versus a one segment or a spliced three segment post-tensioned I-beam. The lateral stability of the beam during fabrication, transportation and erection is also examined and discussed. These tables are intended to aid designers and owners in preliminary project studies to determine if post-tensioning can be beneficial to their situation. In most cases, post-tensioning was found to extend the maximum span length of a typical 72-inch precast I-beam more than 40 feet over conventional prestress.

Keywords: Post-tensioning, Concrete, Precast, I-beams, Prestress, Single span, Bridge, Splice

INTRODUCTION

In the 1950's, precast concrete construction comprised only 2 percent of the bridges in the United States. Today, precast concrete is used in more than 50 percent of the nation's bridges.(12) Economical fabrication costs, quick turnaround, widespread availability, low maintenance, and a long term life cycle are the primary reasons for the successful use of precast. Prestressing is the common choice for reinforcing precast beams; however, prestressing requires an entire span length to be transported in one piece and without intermediate splices. This has limited the span length for this type of construction to a maximum of 160 feet. Although long spans have been constructed using such methods as segmental cantilever construction, cable stays, and segmental arches; these methods require complex analysis, special construction techniques, and custom precast sections, all of which are expensive and do not lend themselves to mass production. However, a new method of precast construction is emerging that extends precast concrete bridge spans into the 160 foot to 300 foot range that was previously dominated by steel plate girders. The construction method overcomes the transportation limitations by utilizing post-tensioning in conjunction with prestress. Combining post-tensioning and prestressing allows multiple sections to be spliced together resulting in longer precast spans.

The most efficient beam cross-section for prestressed concrete is an I-beam configuration. A precast I-beam has a wide top flange, a thinner web, and a wide bottom flange also referred to as the bulb. This bulb enables as many as 70 prestressing strands to be placed in the bottom of the beam to serve as its reinforcement. The same precast I-beam cross-sections can be used when post-tensioning and splicing construction methods are applied. Splicing can be used in single span or multiple span applications.

In a single span post-tensioned bridge, either a single beam or three individual segments are cast with a constant cross-section. Post-tensioning ducts are aligned in a parabolic alignment from end to end of the finished beam. Single segment beams are transported to the site, set on their final supports, and post-tensioned longitudinally. The three-segment construction method utilizes temporary supports. The beams are spliced together in the field atop intermediate temporary supports and post-tensioned longitudinally. See Figure 1.

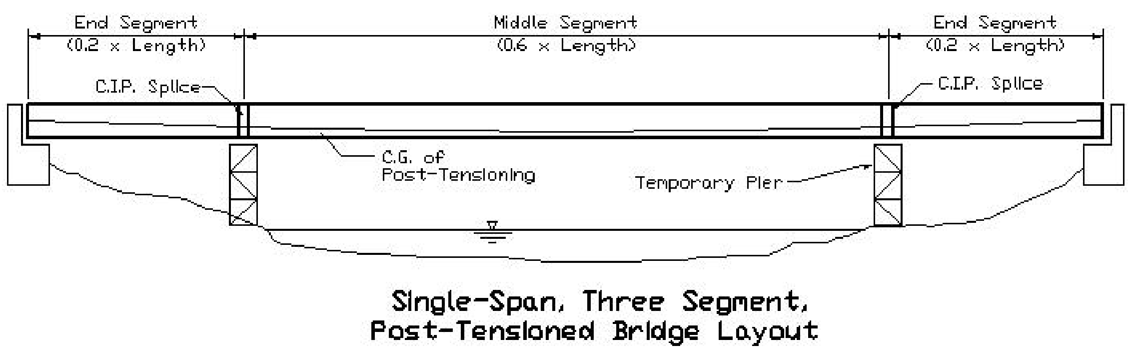


Fig. 1

Multiple span bridges typically utilize precast segments that are continuous over the piers in the negative moment region. This segment is commonly referred to as the pier segment. The segment that connects the pier segments is primarily subjected to positive moment stresses. This segment is often referred to as the “drop-in” section because it is last beam segment to be erected and is then dropped in between the two pier segments. Constructing multi-span bridges in this manner places the splices at the approximate points of contraflexure where the stresses are minimal. The end segments typically span from the abutment to the first point of contraflexure. Utilizing this construction, a typical two-span bridge uses three precast segments along its length, and a three-span bridge uses five segments along its length. An added advantage to this type of construction is that the negative moment section over the pier can be varied or “haunched” to handle the high stresses that result over a pier. Multi-span bridges with continuous beams over the piers can potentially eliminate several, if not all of the temporary supports. This can be accomplished by constructing temporary moment connections to rigidly attach the beams to the pier, then using "strong-backs" to hold the drop-in segment in place until the permanent splices can be made. See Figure 2.

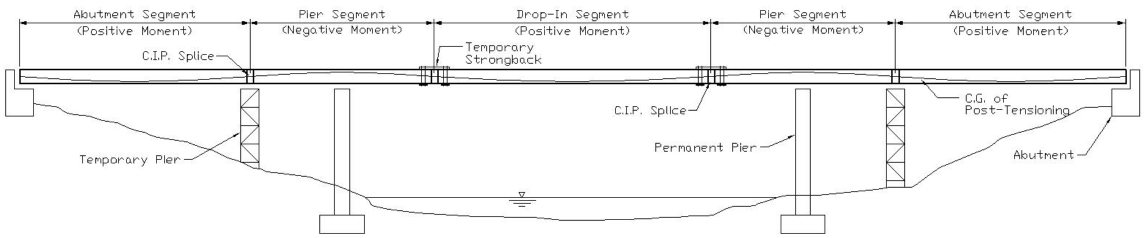


Fig. 2

REPRESENTATIVE PROJECTS

Post-tensioning and splicing of precast I-beams is a technology that has been in use almost as long as prestress; however, it constitutes only 1 percent of the bridges in the United States. Widespread use of post-tensioned concrete beams has been confined to certain regions of the country, such as Florida and Utah. Most states have only a few post-tensioned beam bridges with many having none at all. Owners and designers have been reluctant to use post-tensioning and splicing because it requires a complex analysis, a more skilled contractor, and more complex fabrication and construction techniques. Consequently, it is difficult for owners and designers to assess the economics of such construction methods. Many of the existing post-tensioned beam designs currently in place are there today because they were proven to be the most cost efficient by the contractors. Innovative building procedures such as design build, value engineering, and multiple alternative bidding have allowed this to happen. Contractors, the entities that purchase the materials, pay the laborers, rent the cranes, and build the bridges are often better able to assess the most efficient type of bridge at a particular site. Below are a few examples of such cases.

***Design Build*[13]- *With the 2002 Winter Olympics coming to Salt Lake City, the Utah Department of Transportation (UDOT) realized that it had to replace and widen more than 130 bridges to prepare the Salt Lake City area for the amount of traffic that will result. And it had to be done fast with the strictest of deadlines. UDOT utilized design build to select a designer-contractor team that could meet this deadline at the least cost. One of the challenges to this team was to design 17 single span bridges 210' to 220' in length that would span over single point urban interchanges (SPUI's). Though steel plate girders were considered, the team chose to use spliced precast I-beams to save on cost and reduce fabrication time. The precast I-beams used were 94" deep and spaced over 10 feet apart.*

***Multiple Alternative Bidding*[8,9]- *The Ohio Turnpike needed to replace the twin steel truss bridges that span over the Cuyahoga River Valley. These bridges, each over 2,600* *feet in length and 175 feet over the water at their highest point, were going to be expensive to replace. To control costs, the Ohio Turnpike allowed steel and concrete alternatives to be designed and bid. The concrete alternative utilized spliced beam technology and post-tensioning while the steel alternative utilized plate girders. The winning bid was the concrete alternative at $51.1 million, $1.4 million cheaper than the steel alternative. Of the six contractors who bid the project, four of them submitted bids that were less than the steel alternative. Another important aspect of this type of bidding is that it forces both steel and concrete producers to offer more competitive prices to the contractors compiling the bids since they must also compete with another material. If either steel or concrete had been the only material to bid, the material costs would likely have been higher.*

Value Engineering*[(10)]*- *As part of a project to widen Cincinnati-Dayton Road from two lanes to five lanes, the curved bridge that carries this road over I-75 was to be completely replaced. The original consultant chose to design a four span, curved, steel, plate girder bridge. The consultant likely ruled out prestress I-beams because the middle span length of 130 feet did not allow sufficient vertical clearance over I-75 without significantly altering the existing vertical alignments of either road. The contractor that won the project chose to utilize a value engineering approach so that a precast concrete solution could be used. The contractor's consultant redesigned the bridge using post-tensioned precast beams. Using the same span arrangement and number of beam lines as the steel girder, the precast concrete I-beams were designed without intermediate splices since the 130 foot beams were easily transported. A "kink" at each pier accommodated the curved alignment. Once set into place, the beams were post-tensioned longitudinally for super-imposed dead loads and live loads. Though a special I-beam section was developed employing a 5" thick by 4'-0" wide top flange, the 4'-0" deep I-beam was only 1" deeper than that of the steel plate girder section at the pier in comparison to the original steel alternative.*

A questionnaire was sent out to every state department of transportation to find out about projects in each state that have been designed utilizing post-tensioning and splicing methods. Of the 50 states, 22 states responded to the questionnaire. Of those 22 respondents, 11 states had used post-tensioning and/or splicing with some states having multiple uses. Sixty-Four different questions were asked about the project including geometry, section dimensions, post-tensioning information, splicing techniques and construction methods. Figure 3 summarizes the general characteristics for each bridge. In addition to these bridges, there are many other structures, both in the states that responded, and in states that did not respond. No attempt was made to add these bridges in the results. Nevertheless, the responses received represent a cross-section of applications that demonstrate real uses and benefits of post-tensioning and splicing precast beams.

Summary of State DOT Survey of Bridges
Designed Utilizing Post-Tensioinig and Splicing

State*	Roadway	over	Contract** (DBB, DB or VE)	Spans	Span Length Range	Tallest Pier	Beam Spacing	Beam Depth
Georgia****	N/A	Intercostal Waterway	DBB	20	180'	150'	7.50'	90"
Illinois	40A	FAI 72	DBB	2	106'		6.00'	48"
Louisiana	Colombia	Ouachota River	DBB^{S}	N/A	250'	N/A		72"-120"
Louisiana	Jonesville	Black River	DBB^{S}	N/A	250'	N/A		72"-120"
Louisiana	New Orleans	Rigdlets Pass	DBB	N/A	250'	N/A		72"-120"
Minnesota	T.H. 101 WB & EB	C.S.A.H. 16	DBB^{C}	1	170'	-	5.27'	81"
Nevada*****	N/A	N/A	DBB	2	110'-104'	23'	9.20'	39"
Nevada*****	N/A	N/A	DBB	2	130'-120'	20'	9.50'	51"
North Carolina	US 64	Croatan Sound	DBB	3+	138'-230'	66'	9.91'	78"-132"
Oregon	N/A	Stream	DBB	2	160'	25'	7.83'	84"
Texas ***	US 183	McNeil Road	DBB	3	90'-140'	18'	7.35'	54"
Utah	I-15	4500 South	DB	1	211'	-	10.83'	95"
Virginia	Route 123	Occoquan River	DBB	7	144'-240'	49'	8.79'	N/A
Washington	I-5/SR 20	Cascade Mountains	DBB	1	197'	-	6.89'	95"

N/A Information Not Available

* *Connecticut, Delaware, Hawaii, Maryland, Massachusetts, Montana, New Hampshire, Oklahoma, Pennsylvania and Vermont DOT's also responded but indicated that to their knowledge, bridge projects of this description have been constructed in their state in the last 10 years.*

** *DBB, DB or VE indicates the method of contract. DBB indicates Deign/Bid/Build, DB indicates Design/Build and VE indicates Value Engineering. A superscript letter behind the conctract method indicates that the bridge was bid against a steel alternative. The supersript designates whether Steel or Concrete was the lowest bid.*

*** *Indicates splice only (No post-tensioining)*

**** *Indicates post-tensioning only (No splice other than at pier)*

***** *Indicates U-Beam Section Used.*

\+ *The US64 bridge over the Croatan Sound has three mainspans that are post-tensioned and spliced, there are actually 268 spans in total*

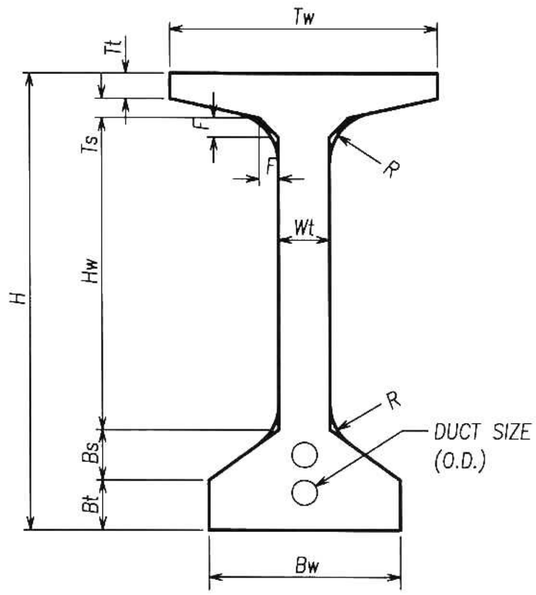
Fig. 3

DESIGN COMPARISON OF PRESTRESS VS. POST-TENSIONING

Post-tensioning and splicing can be used to design a bridge that spans further, uses less girders, and/or has a shallower depth than prestressing alone; however, because of its limited use and complex design, owners and designers are reluctant to use post-tensioning and splicing on a regular basis. The cost of even exploring post-tensioning requires time, effort, and coordination that typical projects usually cannot afford. The objective of this paper is to provide designers and owners with quantifiable limits of what post-tensioning and splicing can and cannot do. With the information and tables developed from this research, designers and owners may be able to more easily determine if post-tensioning is applicable to their particular project at hand.

PARAMETERS

To demonstrate the benefits of post-tensioning, many of the most widely used 72”± deep I-beam precast sections used throughout the country were analyzed using post-tensioning and splicing. This depth was selected because it is commonly used, easily transported, fabrication forms require little modification, and nearly every state is familiar with its limits when used strictly as a prestressed I-beam. Beam sections and their properties are included in Figure 4.



	H (in)	Tw (in)	Tt (in)	Ts (in)	Hw (in)	Bs (in)	Bt (in)	Bw (in)	F/R (in)	Wt (in)
OHIO MODIFIED 72"	72.00	36.00	4.00	2.00	49.00	9.00	8.00	26.00	3.00F	8.00
NEW ENGLAND BT 1800	70.87	47.24	3.35	1.97	52.95	3.94	8.66	31.89	7.87R	7.09
CALTRANS BT 1850	72.83	47.24	3.94	3.74	51.18	5.91	7.87	29.53	7.87R	7.87
AASHTO STD TYPE VI	72.00	42.00	5.00	3.00	46.00	10.00	8.00	28.00	4.00F	8.00
PCI BT 72"	72.00	42.00	3.50	2.00	56.00	4.50	6.00	26.00	2.00F	6.00
COLORADO –BT 72	72.00	43.00	3.00	2.00	54.00	6.00	6.50	26.97	2.00F	7.00
NEBRASKA NU 1800	70.88	48.02	2.56	1.75	50.25	5.50	5.31	39.38	7.89R	6.88
OHIO MODIFIED 60"	60.00	36.00	4.00	2.00	37.00	9.00	8.00	26.00	3.00F	8.00
OHIO MODIFIED 84"	84.00	36.00	4.00	2.00	61.00	9.00	8.00	26.00	3.00F	8.00

	Area (in^2)	Inertia (in^4)	Sb (in^3)	Yb (in)	St (in^3)	Yt (in)	Duct (in)
OHIO MODIFIED 72"	956	616,018	17,893	34.43	16,396	37.57	4.50
NEW ENGLAND BT 1800	958	655,855	19,490	33.65	17,621	37.22	3.94
CALTRANS BT 1850	1063	754,388	20,311	37.20	21,206	35.63	4.50
AASHTO STD TYPE VI	1085	733,320	20,168	36.36	20,576	35.64	4.50
PCI BT 72"	767	545,894	14,915	36.60	15,421	35.40	–
COLORADO –BT 72	864	594,937	16,634	35.77	16,421	36.23	3.94
NEBRASKA NU 1800	924	639,471	19,872	32.19	16,528	38.69	3.75
OHIO MODIFIED 60"	860	384,705	13,386	28.74	12,306	31.26	4.50
OHIO MODIFIED 84"	1052	916,011	22,809	40.16	20,894	43.48	4.50

Fig. 4

Each precast beam section was analyzed on a 48 foot wide bridge at 6-foot, 8-foot, 10-foot and 12-foot beam spacings to determine the maximum span of each precast section using only prestress. Next, each precast section was analyzed again using post-tensioning. For every trial, all dimensions and loadings are held constant. Figure 5 shows the loadings and design parameters used in the analyses. Only beam sections, beam spacings and concrete strengths are varied for comparison.

General Loadings and Bridge Configuration for Comparison of Prestress vs. Post-Tensioning

Live Load	*Greater of: AASHTO HS-25 Truck Load or AASHTO HS-25 Lane Load*
Structural Deck Thickness	*7" (150 lbs/ft^3)*
Sacrificial Wearing Surface Thickness	*1" (150 lbs/ft^3)*
Haunch Thickness	*1" x top flange width (150 lbs/ft^3)*
Crossframes	*None – Assumed steel crossframes, weight is negligible*
Future Wearing Surface (Superimposed)	*25 psf (Distributed evenly to all beams)*
Parapet Load (Superimposed)	*1000 lbs/ft (Distributed evenly to all beams)*
Deck Concrete Strength	*4000 psi*
Beam Concrete Strength	*Concrete #1 – 4ksi @ Release, 6ksi @ Final* *Concrete #2 – 5ksi @ Release, 8ksi @ Final* *Concrete #3 – 6ksi @ Release, 10ksi @ Final*
Strand- Ultimate Stress	*0.5" dia., 7-wire strand, f's = 270 ksi (Initial Pull = 0.75*f's)*
Bridge Width – Out to Out of Deck	*48 ft.*
Bridge Width – Toe to Toe of Parapets	*45 ft. (Two parapets, 1.5 ft wide each)*
Number of Design Lanes	*3 Lanes*
Beam Spacing	*6 ft., 8 ft., 10 ft. and 12 ft.*

Fig. 5

Prestressed I-beams were analyzed using a self-created spreadsheet following design examples from the PCI Bridge Design Manual[11]. Designs involving post-tensioning were analyzed using CONSPLICE PT, Version 1.0[5], a commercial design package developed and maintained by LEAP Software. This proprietary software is specifically used in designing post-tensioning and spliced girder bridges. CONSPLICE PT was also used to evaluate the lateral stability of all prestressed and post-tensioned beams during handling and transportation. AASHTO Standard Specifications[2] were utilized in all cases and ACI-209[4] was utilized to model the effects of temperature, creep and shrinkage in all post-tensioned scenarios.

In all, hundreds of scenarios were analyzed resulting in the 80 or so successful trials recorded in Figure 6. This figure provides the most pertinent information including the maximum span, the area of prestressing used, the area of post-tensioning used, the number of post-tension tendons used and the lowest stability factors of safety for each beam during handling and transportation. For cases where three segments comprise the entire beam, the information given only refers to the middle segment, which was always the most critical segment. Figure 6 is only intended for preliminary use and should be verified using the local codes and procedures in a final design.

Prestressed and Post-Tensioned Beam Results

		6.00 Foot Beam Spacing					8.00 Foot Beam Spacing					10.00 Foot Beam Spacing					12.00 Foot Beam Spacing				
		Span	PS (in^2)	PT (in^2)	FS1	FS2	Span	PS (in^2)	PT (in^2)	FS1	FS2	Span	PS (in^2)	PT (in^2)	FS1	FS2	Span	PS (in^2)	PT (in^2)	FS1	FS2
Ohio 72" (R=4^{ksi} F=6^{ksi})	Prestress	139'	8.18		1.40	1.48	121'	7.35		1.97	1.81	107'	6.68		2.26	1.71	97'	6.35		2.59	1.71
	PT- 1 Seg											126'	4.34	1 @ 4.74	1.12	1.81	116'	4.01	1 @ 4.74	2.81	3.27
	PT- 3 Seg	157'	2.00	2 @ 4.74	6.39	5.78	150'	1.67	2 @ 4.74	7.60	7.38										
Ohio 72" (R=6^{ksi} F=8^{ksi})	Prestress	151'	10.35		1.20	1.39	132'	9.35		1.74	1.78	119'	8.68		1.98	1.65	107'	8.02		2.25	1.82
	PT- 1 Seg											158'	4.34	2 @ 4.74	1.23	1.98	143'	3.67	2 @ 4.74	1.72	2.21
	PT- 3 Seg	182'	5.34	2 @ 4.74	3.81	3.93	170'	4.68	2 @ 4.74	4.66	4.76	154'	3.01	2 @ 4.74	7.61	7.42	140'	3.01	2 @ 4.74	10.6	10.1
Ohio 72" (R=6^{ksi} F=10^{ksi})	Prestress	160'	12.86		1.10	1.47	143'	11.52		1.51	1.72	128'	10.69		1.94	1.94	115'	10.02		2.37	2.24
	PT- 1 Seg																162'	5.68	2 @ 4.74	1.17	1.78
	PT- 3 Seg	200'	7.68	2 @ 4.74	2.89	3.23	188'	7.68	2 @ 4.74	2.90	3.23	177'	7.68	2 @ 4.74	2.90	3.23					
New England BT 1800	Prestress	157'	11.02		1.73	2.28	137'	9.69		2.40	2.66	123'	9.02		3.06	3.14	111'	8.68		3.85	2.96
	PT- 1 Seg											165'	5.01	2 @ 3.98	1.69	2.54	150'	4.34	2 @ 3.98	2.32	3.17
	PT- 3 Seg	185'	5.68	2 @ 3.98	4.74	4.70	173'	5.34	2 @ 3.98	5.65	5.42										
CALTRANS BT 1850	Prestress	158'	11.36		1.50	1.64	139'	10.02		2.06	1.89	125'	9.35		2.59	2.29	112'	8.68		3.02	2.52
	PT- 1 Seg											168'	5.69	2 @ 4.74	1.47	2.28	154'	5.01	2 @ 4.74	1.99	2.73
	PT- 3 Seg	199'	6.68	2 @ 4.74	3.36	2.33	183'	6.01	2 @ 4.74	4.18	3.56										
AASHTO TYPE VI (72")	Prestress	158'	11.69		1.52	1.81	140'	10.52		2.08	2.15	125'	9.69		2.67	2.53	112'	8.85		3.07	2.80
	PT- 1 Seg											168'	6.35	2 @ 4.74	1.45	2.08	152'	5.34	2 @ 4.74	2.03	2.60
	PT- 3 Seg	196'	8.35	2 @ 4.74	3.47	3.23	185'	7.01	2 @ 4.74	4.44	3.94										
PCI BT 72"	Prestress	137'	7.01		1.78	2.16	117'	6.35		2.34	2.60	105'	6.01		2.45	2.78	93'	5.68		2.47	3.12
	PT- 1 Seg																				
	PT- 3 Seg																				
COLORADO BT 72"	Prestress	146'	8.68		1.51	1.70	126'	7.68		2.00	1.86	111'	7.01		2.34	2.08	100'	6.68		2.39	2.19
	PT- 1 Seg											148'	5.68	1 @ 3.98	1.65	2.20	130'	5.34	1 @ 3.98	2.34	3.45
	PT- 3 Seg	186'	4.01	2 @ 3.98	3.90	4.30	170'	3.34	2 @ 3.98	5.33	5.66										
NEBRASKA NU 1800P	Prestress	156'	10.02		2.05	2.98	136'	9.02		2.89	3.58	121'	8.35		3.75	4.29	110'	8.02		4.20	4.67
	PT- 1 Seg											154'	4.34	2 @ 3.37	2.45	3.48	139'	4.01	2 @ 3.37	3.38	4.26
	PT- 3 Seg	178'	4.68	2 @ 3.37	7.65	7.14	166'	4.68	2 @ 3.37	7.65	7.14										
OHIO 60"	Prestress	130'	8.85		1.55	2.94	113'	8.02		2.04	3.42	100'	7.35		2.27	3.72	90'	7.01		2.14	3.84
	PT- 1 Seg	150'	5.34	1 @ 4.74	1.22	3.02	138'	5.01	1 @ 4.74	1.55	3.46	121'	4.34	1 @ 4.74	2.32	4.56	108'	4.01	1 @ 4.74	3.12	5.55
	PT- 3 Seg																				
OHIO 84"	Prestress	170'	11.52		0.87	0.53	151'	10.52		1.23	0.57	136'	9.69		1.53	0.51	122'	9.02		1.78	0.39
	PT- 1 Seg																				
	PT- 3 Seg	201'	5.34	2 @ 4.74	2.94	1.78	184'	4.68	2 @ 4.74	3.89	2.44	170'	4.01	2 @ 4.74	5.86	4.04	156'	4.01	2 @ 4.74	5.87	4.04

FS1 = Factor of safety against failure during initial lifting out of forms. Concrete at release strength.
FS2 = Factor of safety against beam failure during truck transport. Concrete at final (28 day) strength.
PS = Total number of prestress strands used. Each strand area = 0.167 in^2
PT = Total number of post-tensioned strands used. Each strand area = 0.153 in^2

Fig. 6

Graphical comparisons of the prestress maximum span lengths and the post-tensioned maximum span lengths are presented in Figure 7. All 72"± sections were designed using the same concrete strength (Release = 5ksi and Final = 8ksi). This is referred to in the results as Concrete #2.

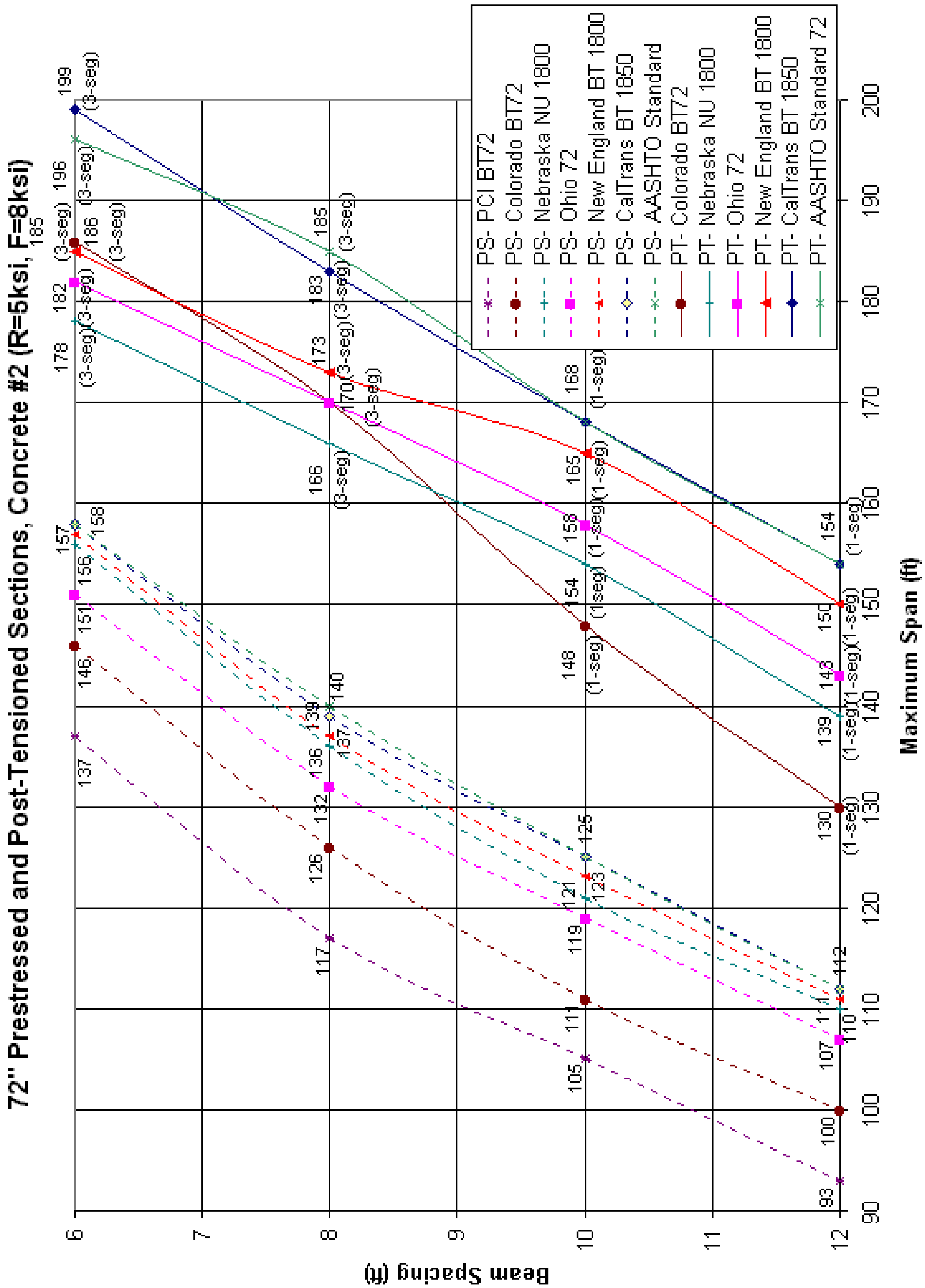


Fig. 7

To

compare the effects of varying the concrete strength, one "weaker" concrete was used (Release = 4ksi, Final = 6ksi) as well as one "stronger" concrete (Release = 6ksi, Final = 10ksi). These are referred to as Concrete #1 and Concrete #3 respectively. Analyses of the different concrete strengths were only performed on the Ohio 72" precast section. The results are shown in Figure 8. With some caution, one could extrapolate these results to other precast I-beam sections by comparing the relative performance of each beam section to those shown in Figure 7.

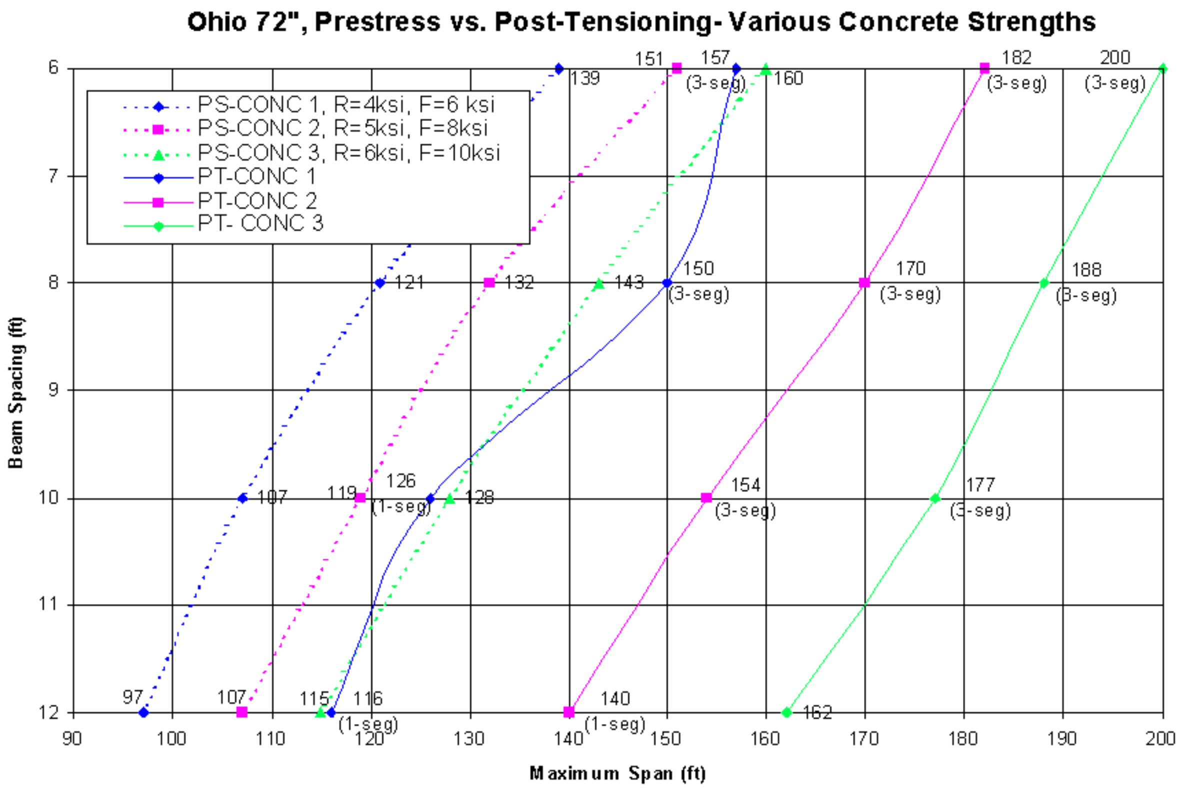


Fig. 8

To compare the effects of varying the beam depth, one shallower and one deeper section were also analyzed for maximum span lengths. All dimensions of the 72" beam flanges were held constant except the web height was decreased and increased by 12 inches. This results in the Ohio 60" section and the Ohio 84" section, respectively. The results are summarized in Figure 9. Again, only the Ohio section was analyzed, but one could extrapolate these results to other I-beams sections by comparison to the maximum span lengths of other 72" I-beams with some caution.

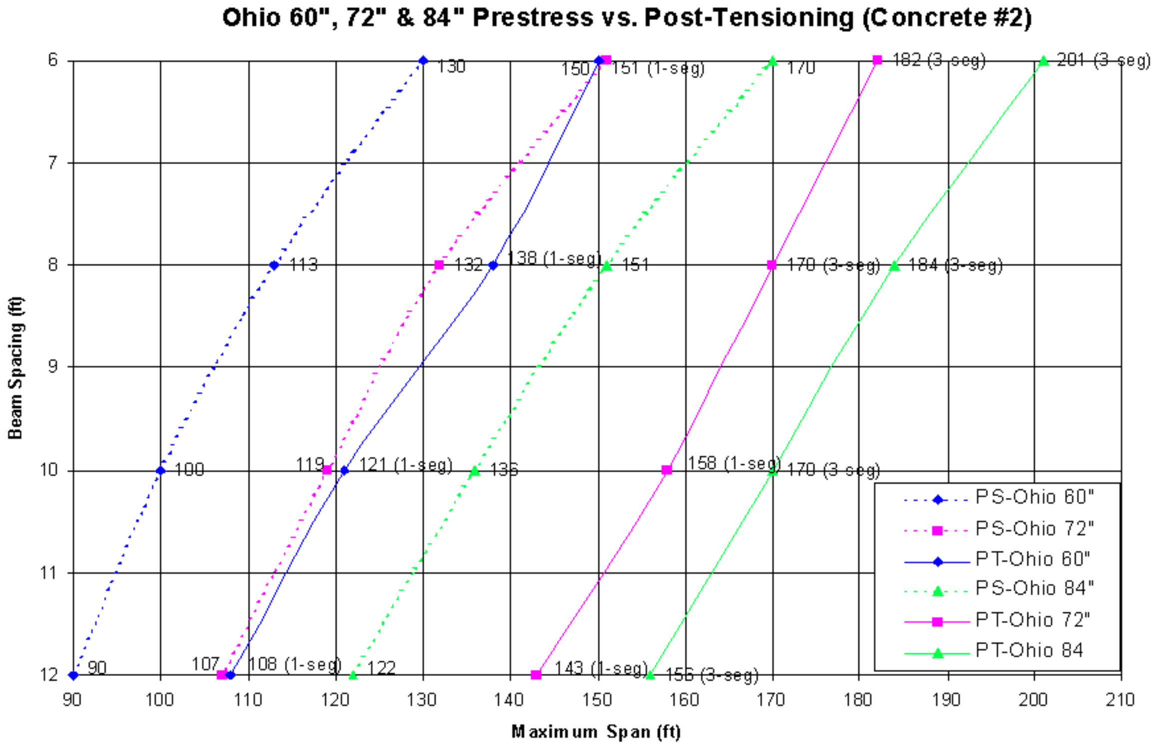


Fig. 9

LATERAL STABILITY

Design of long precast beams, whether prestressed or post-tensioned cannot be properly addressed without consideration of the beam's stability. Instability of the beam during the fabrication, transportation, and erection can result in cracking or failure of the beam prior to the application of any external loads on the beam. Many variables contribute to the stability of a beam. Though it is not the purpose of this paper to go into this subject in depth, certain characteristics of the beam are essential to the stability of the beam. The lateral moment inertia of the beam becomes the important characteristic of the beam as rotation of the beam creates torsion and weak axis bending situations that precast bridge beams may not be designed to handle. Other factors such as the amount of prestressing, the width of the top and bottom flanges, the strength of the concrete and the length of the beam are crucial to the stability of the beam. Typical values of tilt are assumed when evaluating the stability of the beams for this research. A factor of safety of at least 1.5 is typically desirable; although, beams with lower factors of safety can be safely handled by adjusting the location of support, increasing the stiffness of the supports, or utilizing stiffening trusses to name a few. A thorough discussion on the lateral stability of precast beams is described in PCI Journal articles, "Lateral Stability of Long Prestressed Concrete Beams – Part 1 (6) and Part 2 (7)" by Robert F. Mast. The factor of safety for each trial presented in this paper is recorded in Figure 6.

PRESTRESSED CONCRETE I-BEAMS

Prestressed beams are fabricated by first tensioning several high tensile steel strands to approximately three-fourths of its ultimate capacity. Then, concrete is cast around the strands in the desired shape of the beam and allowed to cure to a predetermined strength. Once this strength is achieved, the forms are removed and the prestressing strands are cut beyond the ends of the beams. The cutting of the strands induces compression into the concrete immediately surrounding the strand along its bonded length. Adding compression to the beam at this point will help counteract the tensile forces that will be induced later on, when all the deadloads and liveloads are acting on the beam. The designer may use techniques such as debonding and draping of the strands to prevent over compression in the ends of the beams that will not experience significant amounts of tension.

The design of a prestressed concrete I-beam requires the analysis of the beam's stresses and moments not only once in place but also at the cutting or release of the strands. When the strands are released, the bottom of the beam will be in compression. Once placed in the field and the dead loads and live loads are added, the compression at midspan of the beam in the bottom flange will be reduced, even to the point that the beam experiences a controlled amount of tension. The top flange will experience less compression at release and possibly even tension at the beam ends. As the loads are applied, the top flange at midspan will only increase in compression. The stresses at the midspan and at the endspan must be checked to ensure the allowable limits for tension and compression are not exceeded at any stage of the beam's life. When determining the maximum span for a given beam section in this research, it was always a matter of adding enough strands in the bulb to satisfy the required bottom tensile stresses in its final condition while not exceeding the allowable compressive strength in the bottom of the beam at release.

With the above case always being the limiting factor, the prestress case is rather predictable. When comparing the beam spacing to the maximum span length, fairly consistent curves were generated for every prestressed I-beam investigated. The beams also behaved reasonably proportionate to their respective moments of inertia, See Figure 7. Maximum spans with a 12'-0" beam spacing ranged from 93 feet for the PCI 72" to112 feet for the AASHTO Type VI and the CalTrans 1850. By decreasing the spacing to 6'-0", the maximum span length of these same precast sections increase to 137 feet and 158 feet, respectively.

SINGLE SEGMENT POST-TENSIONED CONCRETE I-BEAMS

Single segment post-tensioned bridge beams are constructed much like typical prestress beams with a few exceptions. Upon fabrication of the beam, hollow ducts are cast into the beam, usually in a parabolic or draped arrangement. The number of ducts typically ranges from one to three, but in some cases even more can be used. These ducts allow an external force to be applied to the beam after the concrete has reached the desired strength. Another general characteristic of post-tensioned beams is the presence of an end block at the beam-ends. An end block is typically as wide as the bottom flange and extends up to the bottom of the top flange. The length of the end block is based upon the amount of post-tensioning force that is to be applied, but typically does not exceed the height of the beam.

Single segment post-tensioned beams are typically prestressed only enough to support their own self-weight and sometimes the non-composite weight of the "wet" concrete bridge deck. The post-tensioned forces are applied by tensioning strands located within the post-tensioning ducts one the beam is in place. Multiple strands typically share the same post-tensioning duct. The strands are secured at one end with a piece of hardware called an anchor. One anchor per duct secures all the strands in the duct. A wedge shaped "chuck" uses the force applied to grip the end of the strand and seat it into the anchor hardware. A similar anchor system is used at the jacking end. All the strands within one duct are often referred to cumulatively as a single post-tensioned "tendon". Ducts are typically pressure grouted after stressing to prevent accumulation of water and corrosion of the strands.

This type of precast concrete beam system has both advantages and disadvantages. The major disadvantages are the complex fabrication of the end block and the extra construction steps in the field necessary to apply the post-tensioned force. Both require the fabricator and contractor to have technical expertise and equipment beyond that required for typical prestress beams. The construction schedule may need to be lengthened to allow time for both of these processes. Contractor and fabricator experience combined with proper planning may substantially lessen the extra time involved.

Though the complications listed above will cause an increase in the cost of design, fabrication and erection, an overall cost reduction may be realized for the project as a whole. Conventional prestress beams are generally limited to 150 foot to 160 foot span length range due to limitations in concrete strength, handling, erecting, and especially transporting such lengths. Though single segment post-tensioned beams are less limited by concrete strength and handling constraints, transportation is still a governing issue. Based upon design capacity and stress calculations alone, single segment post-tensioned I-beams have approximately the same maximum span capabilities as three segment post-tensioned I-beams. As a result, single segment post-tensioned I-beams were not investigated for 6-foot and 8-foot beam spacings since in most cases the span lengths achieved would have been beyond that which could be handled and transported. The particular advantage for the single segment post-tensioned beam construction evident from this research is that the beam spacing can be substantially increased for a given span length, thus eliminating the number of beams required.

For example, the maximum spans shown in Figure 6 indicate that an Ohio 72" prestress beam (Concrete 3, PS = 12.859 in^2) spaced at 6 feet is capable of spanning 160 feet. Similarly, an Ohio 72" single segment post-tensioned beam (Concrete 3, 34 PS = 5.678 in^2, PT = 2 tendons @ 4.741 in^2) is capable of spanning 162 feet and can be spaced at 12 feet. Unfortunately, the factor of safety for handling is below the recommended 1.5 for both configurations at 1.10 and 1.17 respectively. Analyses of these same scenarios at 150 feet show the factor of safety increases to 1.33 and 1.52, respectively. Not only is safer handling achieved with post-tensioning, but only half as many beams are required. The reduction in the number of beams saves in fabrication, transportation and erection, which can result in overall project savings. These advantages may become even more evident on wide bridges, at bridge sites involving long transportation hauls or when multiple bridges are constructed by the same designer, fabricator and contractor team. Construction of multiple bridges using post-tensioning allow the processes to be refined and one-time costs to be lessened on a per beam basis for all parties involved.

The design of the single segment post-tensioned beam must consider several scenarios and time-dependent variables. Each design is checked at various stages of construction. For the 72"± beam sections, two tendons were typically used. The first tendon was pulled prior to the placement of the deck, and therefore, acts on the non-composite beam section only. The second tendon is pulled after the deck has reached its desired strength, and therefore, acts on the composite section. This second tendon is commonly referred to as the liveload tendon as it gives the beam the added capacity to support superimposed deadloads and liveloads. The moment capacity, beam stresses, and deck stresses must not only be checked for the final service conditions, it must also be checked at each stage of construction. Concrete decks typically have a shorter life cycle than the beams that support them. Ensuring that the stresses in the beam will not be exceeded if the deck is removed and replaced sometime in the future is therefore important. Overstress of the beam is possible if a substantial amount of post-tensioning is applied to the beam and deck acting compositely. The concern is that once the deck is removed, the high amount of prestress and post-tensioning may cause intolerable compressive stresses in the bottom of the beam. Overstress when the bridge is redecked was often found to be a limiting case.

The ultimate goal of this paper is to determine the maximum span lengths of the various beam sections. Additionally, evaluating how varying the concrete strength and beam depth affect the various types of precast construction investigated is also important. In the case of post-tensioning, prestress is added to the non-composite section and post-tensioning can be added to the non-composite section, the composite section, or both. Additionally, different amounts of each can be added at the various stages resulting in numerous possible scenarios. To determine which scenario yields the longest span, an Ohio 72" beam was analyzed with many of these varied combinations. From these analyses, the following was found by this author to be most effective manner to maximize the span of a 72"± beam.

First, the use of two tendons yielded the best results. Given the characteristics of the section and material properties, using more than two tendons raises the post-tensioned center of gravity too high to be adequately affective considering the amount of stress (force/area) that is induced into the beam. One tendon does not utilize the full capacity of the section and the concrete while taking up too much area of what would be prestressing strands. Secondly, various trials show that to pull one tendon on the non-composite section and one on the composite section is better. A one time post-tension stressing operation is favorable for construction; however, the prestresss section alone with all available prestress strand locations occupied does not have the capacity to hold the weight of the “wet” non-composite concrete deck at the long lengths these beams can span if post-tensioned otherwise. Additionally, if both tendons are pulled on the non-composite section, excessive compressive stress in the bottom flange prematurely governs the maximum span length. Thirdly, it was sometimes found that a minimum number of prestress strands, sufficient for transportation, was better in combination with the first tendon pull to prevent overstressing the bottom flange in compression. Lastly, for the purpose of maximizing the span, to maximize the number of post-tension strands per tendon and not “hold back” some capacity for a particular stage that may be exceeding stresses before others was generously more advantageous. Adding or subtracting a few prestressing strands better accommodates adjustment of stresses for such purposes.

The limiting factor in prestress beam designs is almost always accomplished by adding enough strands to satisfy Service 1 tensile stresses while not exceeding the compressive stress induced at release of the prestress strands. For post-tensioned beams, it is not as simple, and no one rule always governed. The post-tensioning sequence requires stresses and moments to be checked at multiple times during construction and throughout the life of the beam. Different beam sections and even different beam spacings control at different times in design. Heavier sections were usually controlled by the compression in the redecking stage versus the allowable tension when all loads are present. The lighter sections, such as the Colorado 72” beam, often had little prestress initially. Therefore, tension in the bottom flange at release or compression in the top flange when the wet concrete is added has to be balanced versus the compression in the bottom flange at the redecking stage. In nearly all cases, redecking was one of the limiting stages. Typically, the heavier sections with a larger moment of inertia were easier to design with. Not only were they able to handle the larger post-tensioning forces and span further, but adding or subtracting two prestress strands to fix an overstress in one stage did not dramatically change things in another. This was often the challenge with the lighter sections.

Web thickness was also an important characteristic of each post-tensioned beam section. Duct sizes were chosen that allowed for a minimum cover of 1.5” to be maintained on either side of the web over the duct. Assuming #4 bars are used for the vertical shear reinforcing, only 1” clearance is maintained over these bars. Though these clearances are less than that of a conventional prestressed beam, these clearances have been used successfully in the past. The extra inch in duct size diameter that the tight clearance affords allows significantly more post-tensioning. For the PCI 72” beam, the web only allowed a 3” duct size. As a result of this small duct size, the absence of the prestressing strands in the web area and the low section modulus, the PCI 72” section did not perform well when post-tensioned. Though several analysis were attempted, the maximum span length for the PCI 72” section could not be increased using post-tensioning. Though there is no set rule, increasing the web thickness to a minimum of 8” for all post-tensioned sections would be beneficial. This would allow 1.75” cover over the duct (1.25” over a #4 stirrup) on either side of a 4.5” O.D. duct and would better accommodate the local stresses and shears.

Other scenarios had to be developed for different depths. To represent a shallower section, an Ohio 60” section was analyzed. For this section, a single tendon was found to be most effective. Two fully loaded tendons were beyond the capacity of the section; furthermore, applying the post-tensioning to the non-composite section was more effective than applying this force to the composite section. Though the advantage of applying the post-tensioned force to a composite section is lost, there is still an advantage to applying the external force to a much higher strength concrete than would be for prestress. Also, a significantly lower center of gravity for the post-tension force is maintained. These two characteristics alone allow the maximum span length of an Ohio 60" prestress beam to increase as much as 22% (25 feet). Similar to the Ohio 72" beam, the factor of safety for handling limits the maximum beam length for smaller spacings. For example, stress and moment calculations allow a maximum length of 150 feet for the Ohio 60" section, however the factor of safety for handling is only 1.22. Conversely, handling of the Ohio 60" section at an 8 foot beam spacing (span = 138 feet) is within tolerable handling limits, as well as for larger beam spacings.

Increasing the depth of section was also investigated for the single segment post-tensioned beam. Unfortunately, increasing the depth does little to help the handling and transportation factor of safety for a given section. The maximum span length (143 feet) achieved by the Ohio 72" beam was re-analyzed with the Ohio 84" deep beam (both Concrete 2 and 12' spacing). Though design stresses decreased significantly, the handling factor of safety only increased from 1.72 to 1.78, and the transportation factor of safety decreased dramatically from 2.21 to 1.61. No further analysis was performed on the single segment PT beam using the Ohio 84" deep section as the predictably small increase in length will likely not prove cost effective; however, the Ohio 84" deep section proves most beneficial when the three segment post-tensioned beam is investigated since transportation and handling problems are substantially reduced.

THREE SEGMENT POST-TENSIONED CONCRETE I-BEAMS

Three segment post-tensioned bridge beams are constructed similar to a single segment post-tensioned beam except that that they are fabricated in three discrete sections and assembled at the site. Typically, this is accomplished by pouring a short cast-in-place section in the field between each segment to make one long beam. Three segments allow placement of the splice away from the areas of high moment, tension, and compression. Post-tensioning ducts must be positioned and aligned in such a way that each tendon can be tensioned over the entire length of the beam once the cast-in-place spliced sections have attained their required concrete strengths.

To assemble a three segment post-tensioned I-beam, temporary bents are used to support the individual segments until the field splice is made. Once the connection is made and the cast-in-place sections have achieved their required strength, the first post-tensioning tendon may be pulled. Now that the beam has the capacity to support at least it's own dead load, the temporary bents may be removed. Construction of a three-segment post-tensioned I-beam is also possible on the ground at the jobsite before erection, however beam stability becomes an issue and larger cranes may be required.

There are various ways to splice the segments together in the field. One of the most common is to cast a short 1-foot to 3-foot section in the field. In this cast-in-place section, mild reinforcing and/or prestressing strands, extending from each end of the individual segments, is lap spliced, mechanically spliced, or welded to reinforce this section and provide continuity. Localized post-tensioning is also sometimes used for these purposes. Beam-ends are often designed to be roughened or cast irregular to facilitate shear transfer. The placement of the splice along the beam length is usually around the end quarter points of the beam.

Once the three individual pieces are fabricated, and the cast-in-place field splices are made, the remainder of the construction sequence is identical to that of the single segment post-tensioned beams. The characteristics and design of the spliced beams are, therefore, similar to that of the one-piece post-tensioned beams. An important comparison is to determine whether a one segment post-tensioned beam or a three segment post-tensioned beam can span further with all other things held constant, regardless of transportation issues. For this comparison, an Ohio 72" I-beam with concrete strengths of 5ksi at release and 8ksi (Concrete #2) at final was analyzed at 10 foot and 12 foot beam spacings. It was found that the maximum span differ only one to three feet; therefore, the choice to use a single-segment versus a three-segment should not be based upon which method allows the beam to span further, but should be based upon the lateral stability and ease of transportation of the beam to the site. Consequently, three-segment beams were only analyzed for beam spacings that could not be transported in a single segment. The 72"± three segment post-tensioned beams were analyzed at 6'-0" and 8'-0" spacings. Graphically, one-segment and three-segment results were combined to represent a maximum span length curve for post-tensioning in general.

Similar to one-segment post-tensioned beams, two post-tensioning tendons were generally used to find the maximum span length of the three segment beams. Also like the one-segment post-tensioned beams, the largest possible post-tensioning ducts were used to their full capacity. Prestressing strands were utilized in all three segments sufficient for transportation as a minimum. Additional prestressing strands were added to the middle segment to supplement the post-tensioning and extend the maximum span length. The short end spans typically only required 6 to 8 prestressing strands to facilitate transportation of the beams to the site. The splice itself was not designed as a part of this paper. Considering the location of the splice far from the midspan of the beam, splice details would not be a limiting factor and would have little impact on the maximum attainable span length. Lateral stability or transportation was never an issue for the three segment post-tensioned beams, as the maximum middle segment never exceeded 125 feet.

The three-segment analysis showed that 72"± I-beams typically used for prestressing could be used to span upwards of 180 feet using Concrete #2 (5ksi-Rel & 8ksi-Fin). This same concrete allowed two sections, the Standard AASHTO 72" beam and the CalTrans 1850, to span over 195 feet. In order to determine the effect of different strength concrete used with post-tensioning, the Ohio 72" beam was analyzed using the three different concrete strengths. This comparison shows that the Ohio 72" beam at a 6 foot spacing could be increased from 182 feet to 200 feet by increasing the concrete strengths from concrete #2 (5ksi-Rel & 8ksi-Fin) to Concrete #3 (6ksi-Rel & 10ksi-Fin). Other beams with a greater moment of inertia would likely span further. Similarly, increasing the depth of the beam from 72” to 84” allows the maximum span to increase from 182 feet to 201 feet, both of which used Concrete #2.

CONCLUSIONS

The analyses in this paper demonstrate that post-tensioning can be beneficial and have certain advantages in comparison to prestressing. The following advantages were found regarding 72″ I-beams:

- Post-tensioning of single span precast I-beam bridges can extend the maximum span length by as much as 35% adding more than 40 ft of length to a span.
- Span lengths up to 200 feet for a three-segment, post-tensioned I-beam can be achieved with the combination high strength concrete (10ksi) and a 6-foot beam spacing.
- Half the number of beams can be eliminated by doubling the center-to-center beam spacing in comparison to prestress.
- Increasing the beam depth by 12 inches (84″ deep beam) extends the maximum span length approximately 20 feet for post-tensioning.
- The lateral stability for handling and transportation is improved through the use of post-tensioning, especially when three segments are used.

Additionally, through the process of analyzing many different scenarios, it is possible to develop some general guidelines to aid other designers in maximizing span lengths of post-tensioned I-beams. Though the analyses performed in this paper are primarily based on 72” I-beams, many guidelines are applicable to other situations. These guidelines are as follows:

- Use the largest diameter post-tensioning duct size allowable without violating the necessary cover over the reinforcing steel and duct in the web of the I-beam. Thicker webs allow larger ducts, and therefore, more post-tensioning.
- For a 72″ deep I-beam, two ducts are generally sufficient to maximize the span capabilities of the I-beam section. Additionally, the lower tendon pulled on the non-composite section and the upper tendon pulled on the composite section is generally most beneficial.
- Removal of the deck for a future deck replacement is often a governing load case and should always be considered.
- As with prestressed I-beams, large beam sections with wide top and bottom flanges allow the furthest spans. The wide flanges also improve lateral stability.
- High concrete strengths are recommended, especially final concrete strengths of 8 ksi or more.
- Locating the splice of three-segment, post-tensioned I-beams approximately 20% from either end greatly reduces the moment stresses in the splice.

- Adding additional strands in the middle section of a three-segment, post-tensioned I-beam adds significant capacity to the beam.

Post-tensioning and splicing techniques described in this thesis extend the maximum span range of precast allowing it to be used in many situations it would not otherwise have been considered. The use of post-tensioning and splicing will likely continue to grow as owners, designers, contractors, and fabricators become more familiar with post-tensioning techniques, uses, and advantages. Designers and owners are the key to pushing the use of post-tensioning and splicing in bridge structures as these two entities determine the vast majority of bridge types. Through continued research, experimentation, and use, post-tensioning and splicing precast concrete beams in bridge applications may one day become common practice.

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