PARAMETRIC STUDY OF PRE-TENSIONED GIRDERS REINFORCED WITH 19-WIRE 1-1/8" DIAMETER PRESTRESSING STRANDS

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ABSTRACT

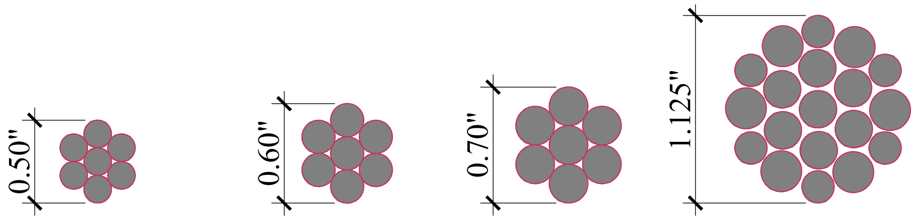
This paper presents a parametric study on the performance, benefits, and drawbacks of employing 19-wire 1-1/8" diameter grade 270 prestressing strands in standard pre-tensioned concrete flexural elements. This study focuses on the performance of various girders, such as the N.U. Girders and Florida I and U Girders, designed using the 1.125-in. diameter strands spaced 3" on center (O.C.) versus 0.5-in., 0.6-in. and 0.7-in. strands spaced 2" O.C. The authors of the study found out that the 1.125-in. strands force per area ratio compared to other diameters allows for a more efficient design provided the same steel grade and high-strength concrete are used. Longer spans can also be achieved by implementing 1.125-in. strands, and a considerable number of strands can be reduced due to the area that the large diameter strand possesses.

Keywords: Precast Concrete, Pre-tensioned Concrete, Large Diameter Strands, Prestressed Concrete Bridge Girders.

INTRODUCTION

Precast concrete building and bridge structures have been built for more than a hundred years. Precast concrete elements range from façade elements to structural components such as columns, slabs, beams, and bridge girders[1–3]. Precast components can be prestressed using high-grade prestressing strands or conventionally reinforced using mild steel. Prestressing has been performed routinely since the late 1930s when Freyssinet understood the significance of losses and implemented approaches to overcome them[4]. In the last 30 years, increasingly large diameter strands have been investigated for use. There has always been reticence when introducing and implementing new strand sizes, and even prohibition of specific sizes in the bridge industry [5]. In recent years, concrete bridges have benefited from larger diameter prestressing strands, which have gone from 0.5 in. to 0.6 in., mostly adopted as the standard in the 1990s. The largest available strands in the United States are 7-wire 0.7 in. diameter strands but are not used as frequently in the country despite several researchers finding that they can provide longer spans and more efficient structures with their use[6–8]. Even larger strands exist in the international market, such as the 19-wire 0.90-in. and 1.125-in. strands. This paper investigates 19-wire 1-1/8 in. diameter strands as another option in pretensioned applications to increase span lengths and reduce the total number of strands.

The 19-wire 1-1/8 in. diameter strand investigated in this paper has a nominal area of 0.825 in^2 and conforms to Japanese Industrial Standard (JIS) G3536:2014[9]. Fig. 1 shows an example of the three most common strand sizes, their dimensions, the cross-sectional area, and the 1.125-in. diameter strand being studied in this paper. Researchers have recently studied bond, transfer, and development length, along with successfully fabricating pre-tensioned large-scale beams using the 19-wire 1.125-in. strand[10]. These researchers determined that current code equations provide conservative estimates for transfer and development length provided high-strength concrete is used. However, more research is warranted to provide a larger sample size of testing and successful applications. Anecdotally, from the experience of the authors, handling the 19-wire strand comparable to past experience with 0.7-in. diameter 7-wire strands, though it is obviously heavier, in spite of the fact that the moment of inertia is much larger. Moreover, the authors and a precast plant recently fabricated two 43-ft. long beams containing two strands with relative ease when compared to 0.7-in. strands as part of on-going research at the University of Nebraska – Lincoln.



A_{ps} = .153 in.^{2} (a)

A_{ps} = .217 in.^{2} (b)

A_{ps} = .294 in.^{2} (c)

A_{ps} = .825 in.^{2} (d)

Fig. 1 Prestressing strand sizes studied: 0.5 in. (a), 0.6 in. (b), 0.7 in. (c), and 1.125 in. diameter strands (d)

The 1-1/8 in. diameter strands contain the same area as 5.4 total 0.5 in. diameter strands and 3.8 total 0.6 in. strands indicating that even if strand spacing must be extended considerably beyond currently typical 2 in. by 2 in. spacing, more prestressing force may be applied per unit area, resulting in higher precompression forces. Table 1 shows a comparison between 1-1/8 in. strand force per area ratio compared to the steel area per concrete area for different spacing, allowing a comparison between strand precompression capability if the same grade steel was used. Clearly, the 1-1/8 in. strand dramatically exceeds the available strands at standard 2 in. by 2 in. spacing, but it is unlikely to be functional with typical concretes at this spacing. However, at 3 in. by 3 in. spacing – the minimum spacing possible given the available chuck diameters – the strand becomes more efficient as compared to 0.7 in. diameter strands.

The goal of this paper is to demonstrate a value proposition for 1.125-in. diameter strands through a parametric study, thus providing non-academic motivation for future research.

Table 1 Comparison of 1-1/8 in. strand at different spacings to other strands at 2 in. by 2 in. spacing

Square Strand Spacing (in.)	Strand		
	0.5in. (0.153 in.^{2})	0.6in. (0.217 in.^{2})	0.7in. (0.294 in.^{2})
2	+439%	+280%	+181%
2.5	+245%	+143%	+80%
3	+140%	+69%	+25%
3.5	+76%	+24%	-8%
4	+35%	-5%	-30%

PARAMETRIC STUDY

This section of the manuscript deals with the parametric study of pre-tensioned concrete girders. This study aims to determine the reduction in strand number and determine the maximum achievable spans for each strand diameter. To accomplish this, six different standard bridge shapes were employed, namely the NU1800, NU2000, FIB-84, FIB-96, FUB-63, and FUB-72. The parameters employed in the study are summarized in Table 2 and the section properties in Table 3. The girders' design was performed using the 8th Edition of the AASHTO LRFD Bridge Design Specifications[11], which included evaluating stresses for the Strength I, Service I, Service III, and Transfer limit states. The girders' nominal capacity in flexure was computed using a strain compatibility analysis, and the losses were estimated using the AASHTO detailed method. In shear design, only the girder's maximum capacity was evaluated to ensure that the span was achievable. Fig. 2 shows the typical girder shapes, and the maximum number of strands of a single type were considered in the parametric study. For the prototype bridge under consideration, the spacing of the NU. and FIB girders was 8-ft. O.C., whereas the spacing of the FUB girders was 12-ft. O.C. For all cases, the girders' concrete strength at release, *f'ci*, was 8 ksi, and the concrete compressive strength at 28 days, *f'c,* was 10 ksi, whereas the concrete strength of the deck *f'cd* was 4 ksi.

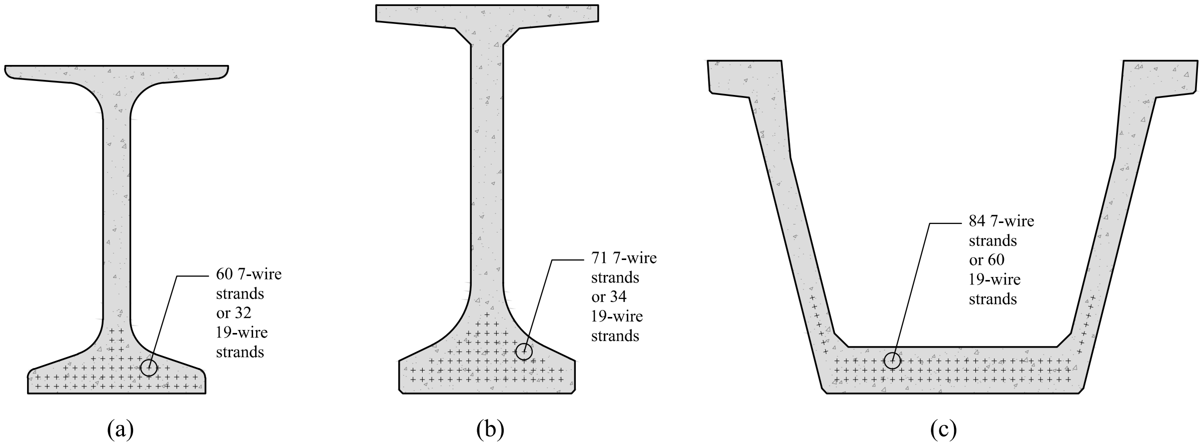


Fig. 2 Types of girders used in the study: N.U. Girder (a), Florida I girder (b), and Florida U girder. The concrete cover from the bottom fiber to the first line of strands in N.U. Girders were 1.5-in. and 2.0-in., for the 7-wire and 19-wire strands, respectively, whereas 3 inches for the FIB girders, and 3-in. and 2-in. for the FUB girders*.

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* Only 7-wire strand patterns at 2-in. on center (O.C.) are displayed in the figure for simplification purposes. The spacing of 19-wire strands was 3-in. O.C. in the cases not pictured.

The simple span bridge's live load was computed using the HL-93 standard truck, and the distribution factors were computed considering the limitations in the code for each of the shapes used. A New Jersey type barrier of 0.100 kip/ft/girder was considered, whereas a 1-in. haunch and a 2-in. wearing surface were employed in the dead load analysis. The beam diaphragms employed in the analysis were made of steel; thus, their weight was considered negligible for calculation purposes. All design scenarios were carried out using a parametric tool developed using well-stablished spreadsheets[8] with formulas and macros to facilitate the process's automation. Losses were computed using AASHTO recommendations in all cases.

Strand spacing investigated was 2 in. by 2 in. spacing for the 7-wire strands and 3 in. by 3 in. spacing for the 19-wire strand. As described above, this tight spacing for the 1.125-in. diameter strand has yet to be established experimentally, but this spacing represents the tightest spacing possible given the known stressing hardware. To establish an efficient use-case for these large diameter strands, it is – for now – assumed that such tight spacing is possible. Such research is ongoing, and high strength concrete and Ultra-high-performance concrete may be required for successful implementation.

Table 2 Properties of the bridge components and materials used

Properties	Girders	*f'ci, ksi*	8
		f'c, ksi	10
		Eci, ksi	5098,
		Ec, ksi	5700
		wc, pcf	150
		Length	40 to 200
		Spacing	8 and 12
		Number	6
		Type	Interior
	Deck	*f'c, ksi*	4
		Ec, ksi	3605
		wc, pcf	150
		t, in.	8 (7.5 structural)
	Prestressing Steel	*fpu, ksi*	270
		fpj, ksi	202.5
		Eps, ksi	28500
		Diameter Size, in.	0.5, 0.6, 0.7, 1.125
	Mild Steel	*fy, ksi*	60
		fu, ksi	90
		Es, ksi	29000

Table 3 Section properties of the girders employed in the study

Section	Height (in)	Web Width (in)	Top Flange Width (in)	Bottom Flange Width (in)	Area (in^2)	Y_b (in)	Y_t (in)	I (in^4)	Weight (kips/ft)
NU 1800	70.9	5.90	48.2	38.4	857.30	32.0	38.9	611,328	0.89
NU 2000	78.7	5.90	48.2	38.4	903.80	35.7	43.0	790,592	0.94
FIB-84	84	7.0	48.0	38.0	1142.58	37.34	46.66	1,087,000	1.19
FIB-96	96	7.0	48.0	38.0	1226.58	42.82	53.18	1,515,000	1.28
FUB-63	63	-	-	-	1377.00	25.92	37.08	659,103	1.43
FUB-72	72	-	-	-	1479.00	29.91	42.09	933,707	1.54

RESULTS

This section presents the parametric study results, which provide insight into the effectiveness of using 19-wire 1.125-in. diameter strands to reduce the number of strands. The results plotted herein are later discussed, and recommendations are given for future steps towards implementing these strands. Fig. 3, Fig. 4, and Fig. 5 show the required strands by design versus the span lengths for 0.5-, 0.6-, 0.7-, and 1.125-in. diameter strands in six different precast, pre-tensioned concrete bridge girders. The transverse spacing was 8 ft. for all girders except for the FUB shapes, which were designed using a spacing of 12 ft. For spans longer than 100-ft., the design's controlling case was Service III, whereas shorter spans were the strength design. The limits on the stresses were taken from AASHTO LRFD 8th Edition Tables 5.9.2.3.1b-1, 5.9.2.3.2a-1, 5.9.2.3.2b-1, and are displayed in Table 4. In all cases, there was a direct relationship between the strand size and the maximum reachable span length by the concrete girder, whereas the number of strands also decreased for a given design span and strand size. Live load deflection limit of L/800 did not control in any cases.

Table 4 Stress Limits Implemented in the Study

Bottom Fibers		Top Fibers			
Initial	Final	Initial	Final I	Final II	Final III
$0.60f'_{ci}$	$-0.19\sqrt{f'_c}$	$-0.24\sqrt{f'_{ci}}$	$0.45f'_c$	$0.60f'_c$	$0.40f'_c$

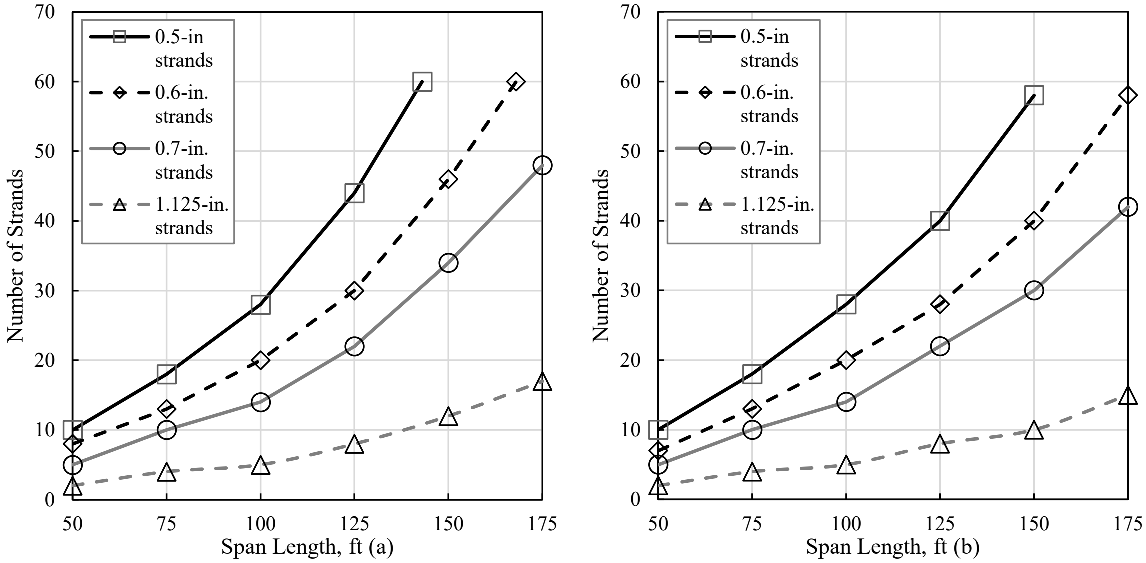

Fig. 3 Variation in strand number versus span length for NU1800 (a) and NU2000 (b) Bridge Girders

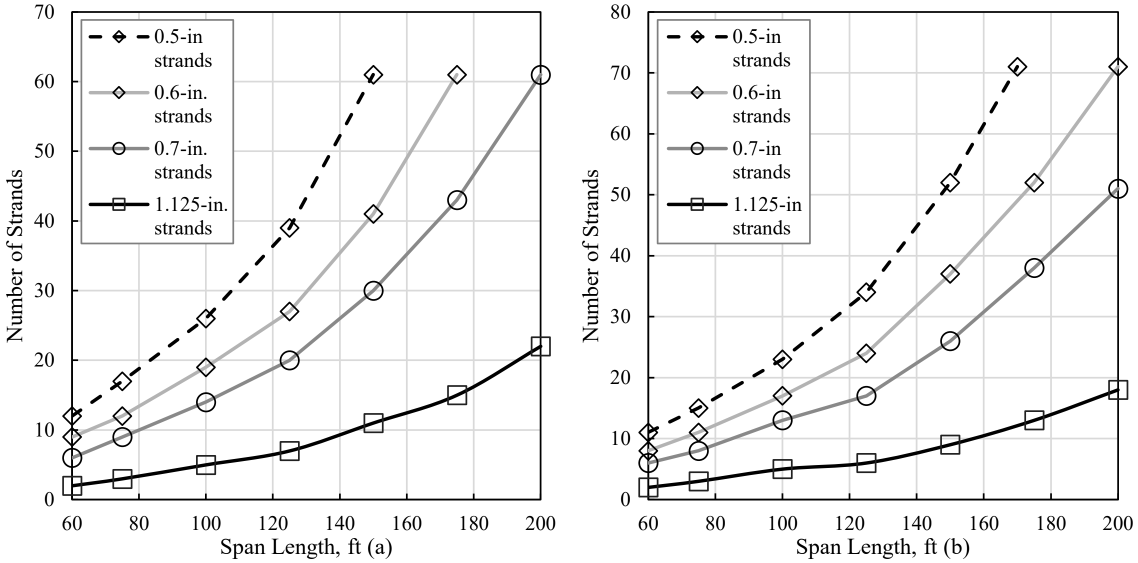

Fig. 4 Variation in strand number versus span length for FIB-84 (a) and FUB-96 (b) Bridge Girders

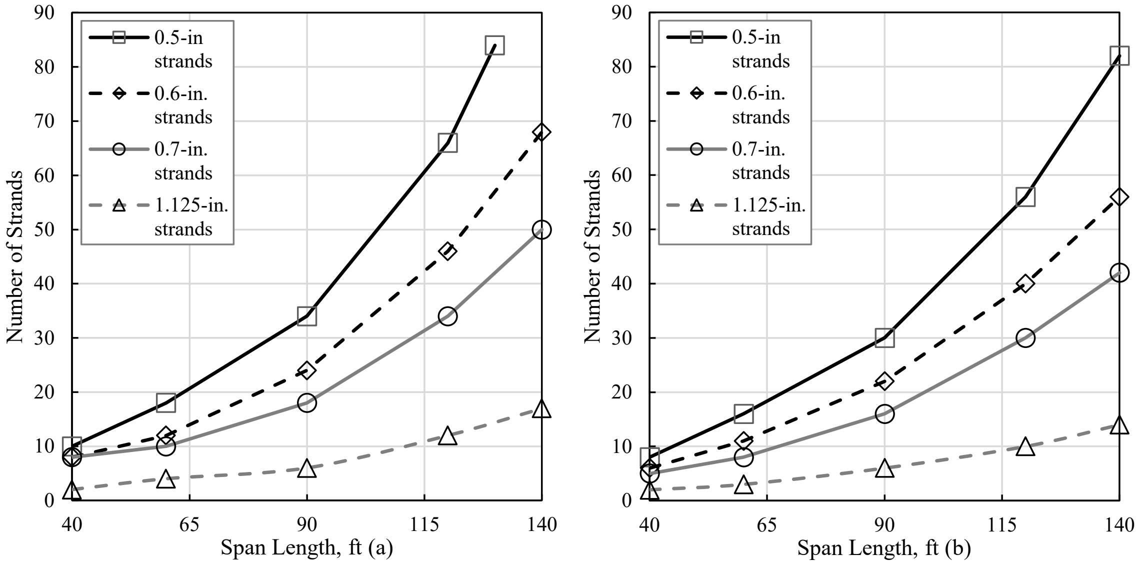

Fig. 5 Variation in strand number versus span length for FUB-63 and FUB-72 Bridge Girders

DISCUSSION

The maximum attainable spans for each strand are displayed in Table 5 for all girders and the different strand sizes. As can be seen, there is a positive correlation between the strand size and the maximum span that can be reached when switching from one size to the other. In other words, the maximum attainable span length for a given pre-tensioned girder increase as one moves from one strand size to the other; however, increasing the number of large diameter strands also increases the precompression force drastically from a given amount to the other (0.825in.^{2} per strand) which can lead to exceeding the initial limit on compressive stress at release.

Table 5 Evaluation of span increase with an increase of the strand diameter

Girder	0.5-in.		0.6-in.		0.7-in.		1.125-in.	
	Span	Strands	Span	Strands	Span	Strands	Span	Strands
NU 1800	143	60	168	60	175	48	182	18
NU 2000	175	58	175	58	195	54	203	21
FIB-84	150	61	175	61	205	71	215	26
FIB-96	170	71	200	71	215	71	230	26
FUB-63	130	84	153	84	175	84	168	29
FUB-72	140	82	164	84	187	84	200	34

In the case of strand number reduction, using 19-wire 1.125-in. strands leads to a tremendous decrease in the quantity needed to reach a given span. Table 6 Shows the strand reduction for all the studied girders and a span length of 150 ft. As can be seen, the number of strands employed for reaching this span can be reduced by at least 19 strands in the case of 0.7-in. strands and as high as 68 strands for the case of 0.50-in. strands. The least benefited girder in all cases was the N.U. girder since its dimensions are optimized for 0.7-in. strands, and they use the lowest concrete cover of the whole group (1.50 in. to the center of the 7-wire strands. The most benefited girder of the group was the FUB, for which the number of strands that can be placed is also more massive than the other girders due to its wider and thicker bottom flange. Another benefit from a significantly reduced number of strands may be decreased end zone congestion, assuming bursting reinforcement increases are unnecessary.

Moreover, when comparing the gross amount of reinforcement needed to achieve a certain span length, it was found that shorter spans do not benefit from using 1.125-in. strands. As Fig. 6 through 11 show, in 50% of the cases, using these new strands will result in more steel than other strand sizes. When one moves from the 50-60 ft. range to the 100-200 range, it becomes more apparent that the shape used influences the amount of steel that a designer could save because of the resulting reinforcing pattern. This is logical because for a deeper section, the greater the nominal resisting moment strength. In such cases (long spans), the amount of reinforcement saved is roughly estimated at 5-7% for the FIB-96 and FUB-72 shapes. However, it is not the case for the other shapes, especially for the N.U. shapes, where the reinforcement needed increases in almost all cases. This is a geometry problem rather than a strand problem because the bottom flange of most concrete shapes was conceived to accommodate strands at 2-in. O.C. spacing rather than the odd spacing of 3 in. for the 1.125-in. strands. Therefore, new beams may need to be created and investigated to accommodate such a large strand size.

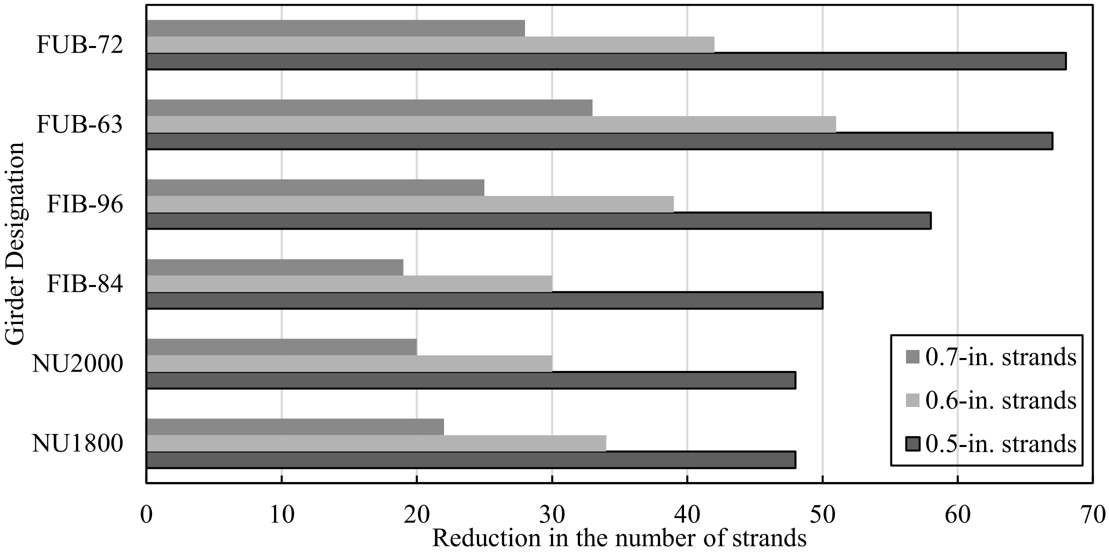

Fig. 6 Reduction in the number of strands per girder type for a span of 150 ft.

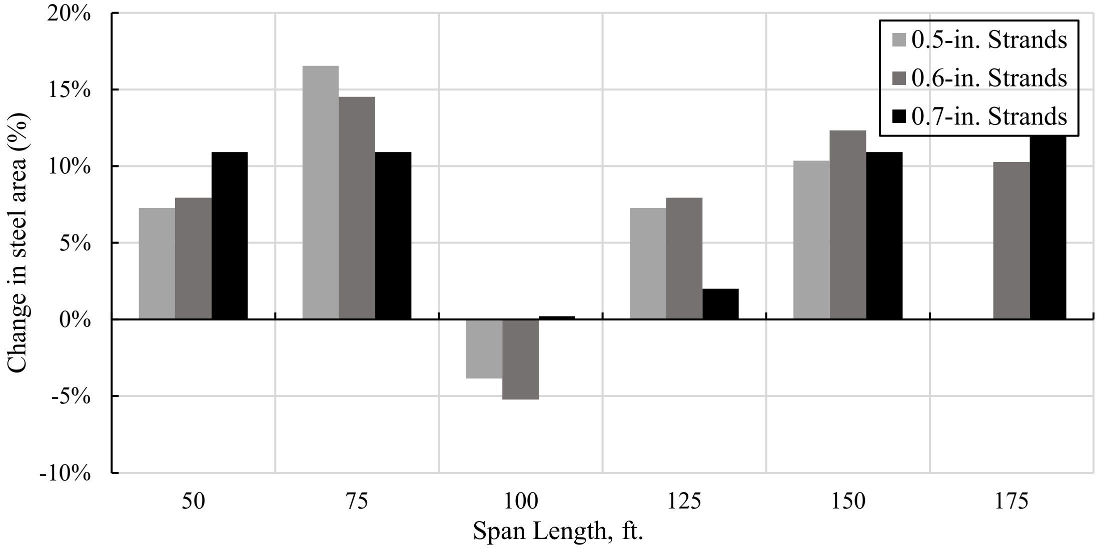

Fig. 7 Percent change in steel area for a NU2000 shape compared to 1.125-in. strands. Positive change indicates additional steel used and negative means savings.

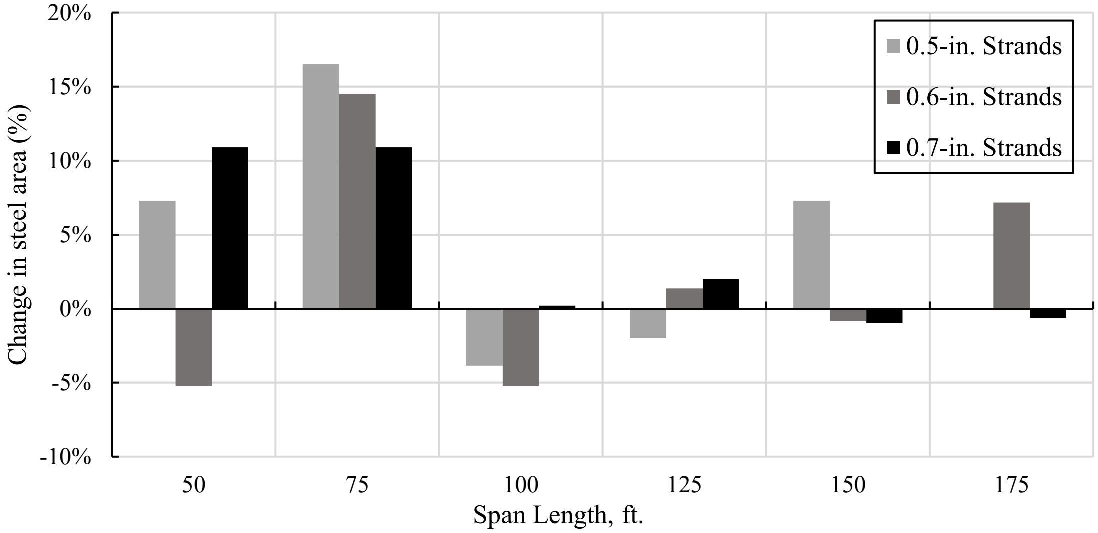

Fig. 8 Percent change in steel area for a NU1800 shape compared to 1.125-in. strands. Positive change indicates additional steel used and negative means savings.

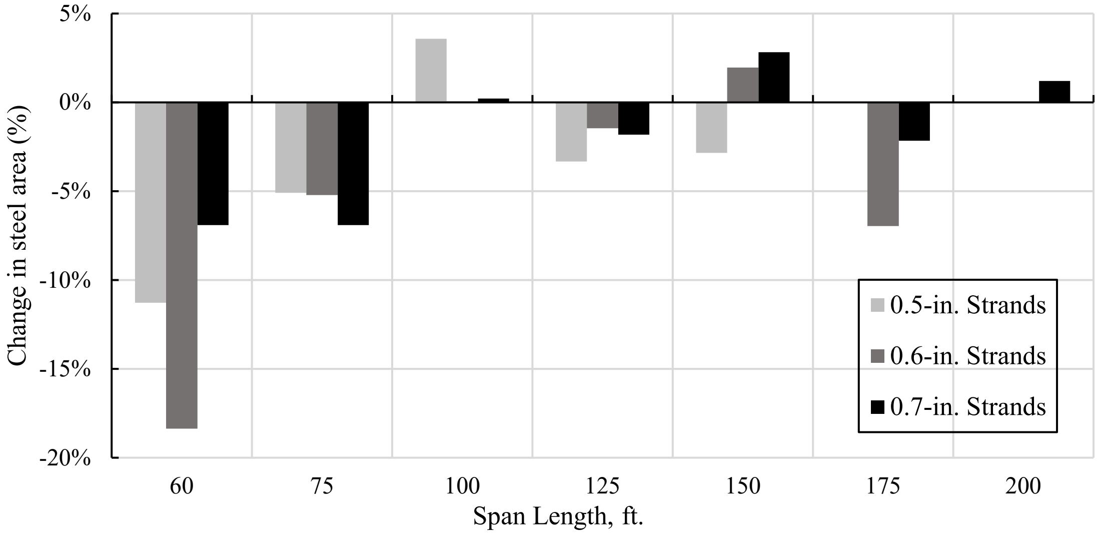

Fig. 9 Percent change in steel area for an FIB-84 shape compared to 1.125-in. strands. Positive change indicates additional steel used and negative means savings.

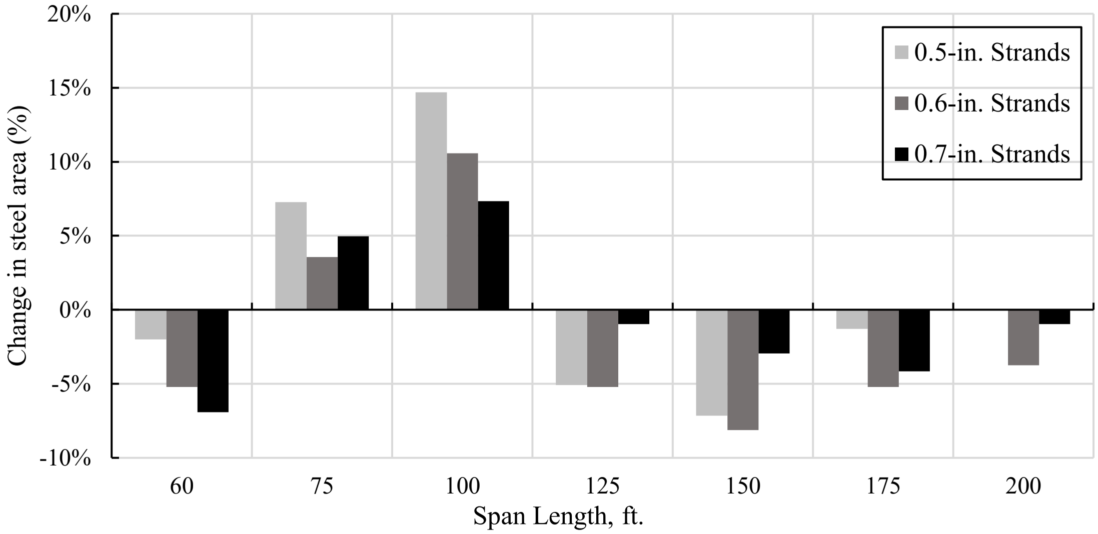

Fig. 10 Percent change in steel area for an FIB-96 shape compared to 1.125-in. strands. Positive change indicates additional steel used and negative means savings.

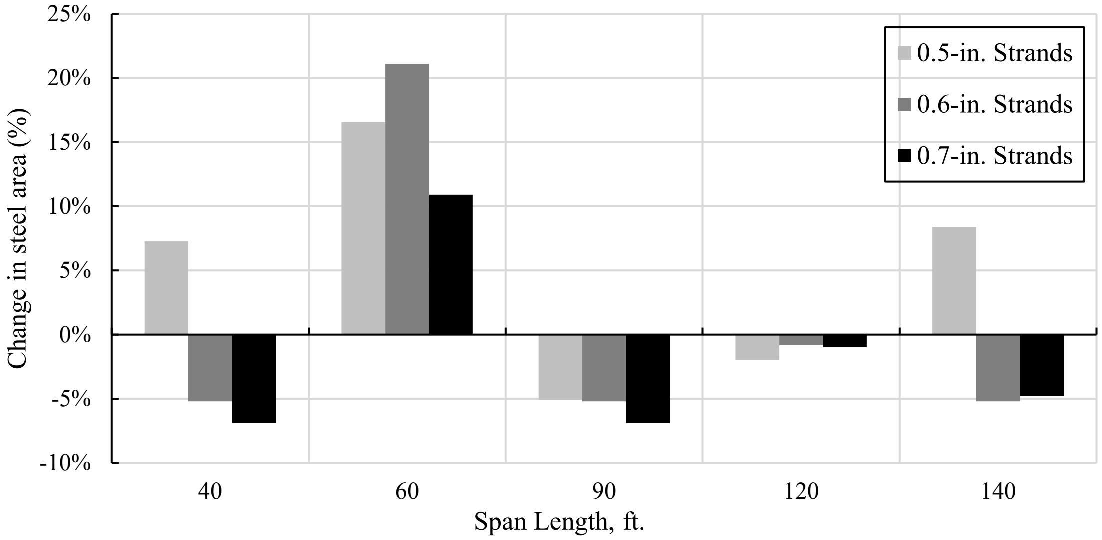

Fig. 11 Percent change in steel area for an FUB-68 shape compared to 1.125-in. strands. Positive change indicates additional steel used and negative means savings.

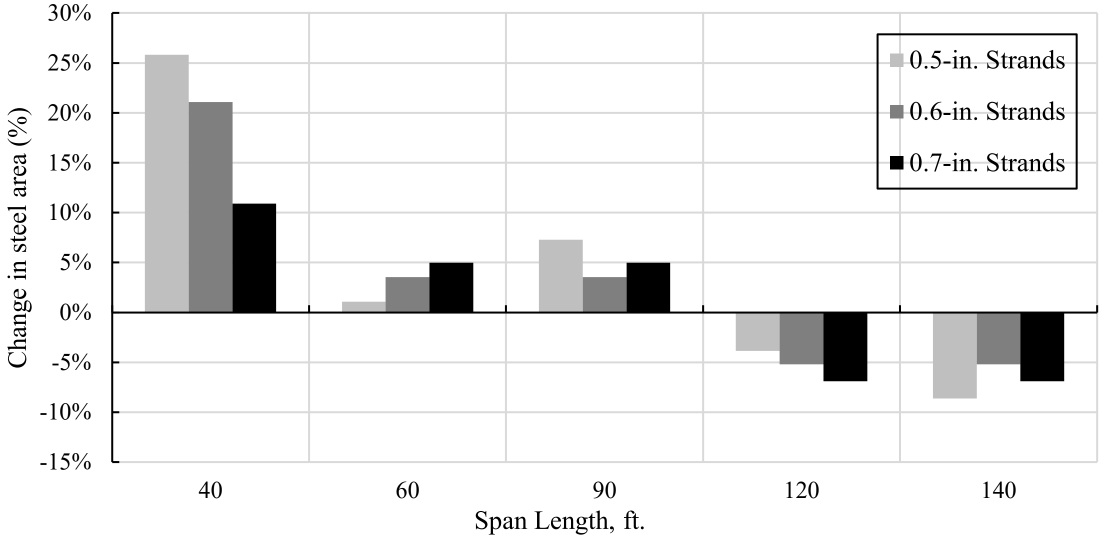

Fig. 12 Percent change in steel area for an FUB-72 shape compared to 1.125-in. strands. Positive change indicates additional steel used and negative means savings.

CONCLUSIONS

A parametric study was performed to evaluate the potential benefits obtained from using 1.125-in. strands in pre-tensioned applications for flexure members. Over 100 design cases were performed to evaluate the benefits of using this strand size, and comparisons were drawn. The main findings of the study are summarized as follows:

- Implementing 19-wire 1.125-in. diameter strands dramatically reduces the number of strands due to their large area compared to 0.50-, 0.60-, and 0.7-in. strands. The reduction in the number of strands ranges from 2 to 68 strands, where 2 is the case of short spans (40 to 60 ft. long spans), and 68 in long-span bridges (more than 75 ft. long spans).
- Longer span bridges (100-200), benefit more from large diameter strands than short span bridges. In most cases, the savings are in the range of 5-7% but may be optimized if mixed with other sizes.
- FUB shapes, because of their geometry, can accommodate more strands and benefit more from the 1.125-in. than most shapes in the case of long-span bridges.
- NU shapes are not compatible with the large-diameter strands, as the amount of steel increases in most cases when implementing them.
- The maximum span achievable with 1.125-in. diameter strands at 3 in. by 3 in. spacing is 203, 230, and 200 ft. for the NU 2000, FIB-96, and FUB 72, respectively (the deeper section of each). This is compared to the use of 0.5 in. strands, which results in 58, 71, and 82, respectively; 0.6 in. strand at 2x2 spacing at 58, 71, and 84 respectively; and 0.7 in. strands at 54, 71, and 84, respectively.
- More research is needed to safely employ this strand size in pre-tensioned flexural members' applications, including their implementation in UHPC flexural members, which may provide an effective balance and even tighter strand spacing.

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