Benefits of using 0.7 in. (18 mm) diameter strands in precast, pretensioned girders: A parametric investigation

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- This paper presents a parametric study on the benefits and limitations of using 0.7 in. (18 mm) diameter strands in precast, pretensioned concrete bridge girders.
- A validated parametric study tool was used to design a variety of girders with 0.5, 0.6, and 0.7 in. (13, 15, and 18 mm) diameter strands using different span lengths, concrete release strengths, and transverse spacings.
- The most noticeable benefit of 0.7 in. (18 mm) diameter strands over 0.6 in. (15 mm) diameter strands was found to be a reduction of up to 35% in the number of strands.

The use of 0.5 and 0.6 in. (13 and 15 mm) diameter prestressing strands is common practice in the precast concrete industry. However, in recent years, there has been considerable interest in using larger-diameter strands to reduce the fabrication costs and extend the span capabilities of pretensioned concrete elements. Increasing the diameter and therefore the cross-sectional area of strands leads to fewer strands being needed to provide the same area of prestressing steel. Moreover, using larger-diameter strands makes it possible to place greater steel area closer to the tensile face of a pretensioned girder, which results in a greater internal moment arm within the cross section. Therefore, the flexural capacity of any given pretensioned elements is expected to increase when larger-diameter strands are used. In addition, the nominal shear capacity is expected to increase due to increased effective shear depth. Such an increase in the capabilities of pretensioned elements enables more-slender superstructures for bridges and improves the competitiveness of pretensioned-girder bridges with steel bridges.

In recent years, the aforementioned benefits have caused a significant increase in the use of 0.6 in. (15 mm) diameter strands instead of 0.5 in. (13 mm) diameter strands. For example, in Texas, while only 0.5 in. strands were used in pretensioned girders fabricated during the early 1990s, the majority of pretensioned girders currently fabricated employ 0.6 in. strands.

In 2008, 0.7 in. (18 mm) diameter prestressing strands were introduced to the pretensioned concrete industry (**Fig. 1**). With a cross-sectional area 35% greater than that of 0.6 in. (15 mm) diameter strands and 92% greater than that of 0.5 in. (13 mm) diameter strands, 0.7 in. strands have the potential to provide significant benefits compared with the prestressing strands currently used in practice. However, the precast concrete industry has been apprehensive about using 0.7 in. strands, and the real-world application of these strands has been limited.

To identify the current status of using 0.7 in. (18 mm) diameter strands in pretensioned girders, a nationwide survey of all state transportation departments was conducted in 2015. Responses received from 27 states revealed that there is a general lack of experience with 0.7 in. strands in the United States, with the only reported cases of using these larger-diameter strands being in two pretensioned-girder bridges in Nebraska. Common reasons mentioned for not considering the use of 0.7 in. strands or for choosing to continue using smaller-diameter strands included the lack of published research on the behavior of girders with larger-diameter strands, the limited availability of the strands and accessories, required facility upgrades at precasting plants, and potential safety and handling considerations. Moreover, questions were raised regarding the benefits of increasing the span capabilities of pretensioned girders, given the shipping limitations.

Widespread implementation of 0.7 in. (18 mm) diameter strands in the pretensioned industry may require a considerable initial investment. A variety of components in prestressing facilities, such as hydraulic equipment, anchorage and hold-down devices, and foundations, may need upgrades to accommodate the larger forces applied to 0.7 in. strands. Furthermore, extensive research is needed to investigate the characteristics of these larger-diameter strands in terms of transfer and development lengths and the potential effects of using these larger-diameter strands on the serviceability and ultimate limit state performance of pretensioned girders. The potential facility upgrades and conducting research on the behavior of girders employing 0.7 in. strands are feasible if the benefits of using these larger-diameter strands outweigh the initial investment. Therefore, quantitative assessment of the potential benefits and limitations of using 0.7 in. strands is essential in making decisions regarding the potential use of these larger-diameter strands in the precast concrete industry.

A number of studies have been conducted on the behavior of pretensioned concrete elements in which 0.7 in. (18 mm) diameter strands are used as the prestressing steel.[1–9] These studies have focused primarily on the constructability issues related to the use of these larger-diameter strands, measurements of transfer and development lengths for 0.7 in. strands, overall structural performance of pretensioned girder specimens in which 0.7 in. strands are used, or a combination thereof. However, previous studies aimed at quantifying the potential benefits obtained from using 0.7 in. strands have been limited. A brief parametric study of this problem was conducted by Vadivelu.[1] In this study, the effects of using 0.7 in. strands on the span capabilities and required number of strands within NU girders[10] and AASHTO I-girders[11] were evaluated. The sections investigated included NU1350, NU1800, and AASHTO Type V and Type VI. Three compressive release strengths of 10, 15, and 28 ksi (69, 100, and 190 MPa) were considered. The use of 0.7 in. strands compared with 0.6 in. (15 mm) diameter strands resulted in an increase in the span capability of AASHTO Type V girders by 17%. The same maximum span of 140 ft (43 m) could be achieved with AASHTO Type VI with 0.6 in. strands and AASHTO Type V with 0.7 in. strands, which emphasizes a possible reduction in the section size when employing 0.7 in. strands. Increasing the compressive release strength of concrete from 10 to 15 ksi resulted in an increase in the span capability of girders employing 0.7 in. strands by 8.5%. However, no further increase was observed in the span capability of the girders when the compressive release strength was increased from 15 to 28 ksi.

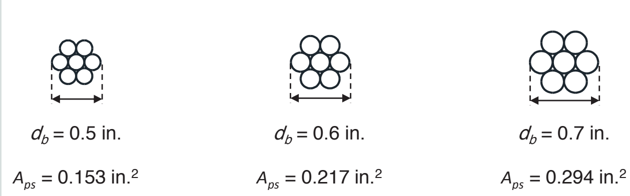

Figure 1. Cross sections of 0.5, 0.6, and 0.7 in. diameter strands. Note: A_{ps} = cross-sectional area of prestressing strand; d_b = strand diameter. Note: 1 in. = 25.4 mm.

As part of an effort to develop preliminary design charts for NU girders, Hanna, Morcous, and Tadros[12] conducted parametric designs of NU girders with 0.6 in. (15 mm) and 0.7 in. (18 mm) diameter strands based on the fourth edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[13] The spacing between girders varied from 6 to 12 ft (1.8 to 3.7 m), and the compressive strength of concrete ranged from 6 to 11 ksi (40 to 76 MPa) for girders with 0.6 in. strands and from 9 to 11 ksi (60 to 76 MPa) for girders with 0.7 in. strands. The use of 0.7 in. strands was reported to result in a general increase in the span capability of the NU girder and a decrease in the number of required strands. The design of girders employing 0.7 in. strands was found to be governed by stresses at the time of release, whereas AASHTO LRFD specifications[13] Service III load combination controlled the design of girders employing 0.6 in. strands. In a separate publication, Morcous, Hanna, and Tadros[3] reported the number of required strands and the span capability of the NU900 cross section when employing 0.6 and 0.7 in. strands. The compressive strength of concrete at release varied from 6 to 11 ksi, and spacing between the girders ranged from 6 to 12 ft. The use of 0.7 in. strands was reported to require a minimum concrete release strength of 11 ksi, as opposed to 0.5 in. (13 mm) and 0.6 in. diameter strands requiring 6 to 8.5 ksi (40 to 59 MPa). The number of 0.7 in. strands needed was approximately 40% and 60% less than that of 0.6 and 0.5 in. strands, respectively. For a given girder spacing, an increase in span length of 15 to 20 ft (4.6 to 6.1 m) was reported when the girder employed the same number of 0.7 in. strands instead of 0.6 in. strands.

Although these studies provide valuable insight into the potential benefits of using 0.7 in. (18 mm) diameter strands, several critical aspects of this problem have not been sufficiently investigated. Most important, all previous studies have been limited to a few types of NU girders and AASHTO I-girder or bulb-tee sections. The benefits and limitations of 0.7 in. strands need to be studied in a wider variety of precast, pretensioned concrete cross sections. Moreover, in none of the previous studies has the entire set of design parameters, including stresses at the time of release, service-level stresses, ultimate strengths in flexure and shear, deflection limits, harping requirements, and shipping restrictions, been investigated holistically.

Considering these gaps in the literature, this paper presents a comprehensive parametric study on the benefits and limitations of using 0.7 in. (18 mm) diameter strands in pretensioned bridge girders, with a primary focus on the precast concrete sections used in Texas. The overall methodology of the study is introduced first, followed by an introduction to a parametric study tool that was used for the investigation. Next, the assumptions, including the selected design parameters and configurations, will be introduced. Finally, the results of the parametric investigation will be presented and discussed to evaluate the extent to which the use of 0.7 in. strands can improve the efficiency of precast, pretensioned concrete girders.

Methodology of investigation

To evaluate the benefits and limitations of employing larger-diameter strands, a simple bridge configuration consisting of straight pretensioned concrete girders was considered. The girders were designed using 0.5, 0.6, and 0.7 in. (13, 15, and 18 mm) diameter prestressing strands, assuming a variety of combinations for the

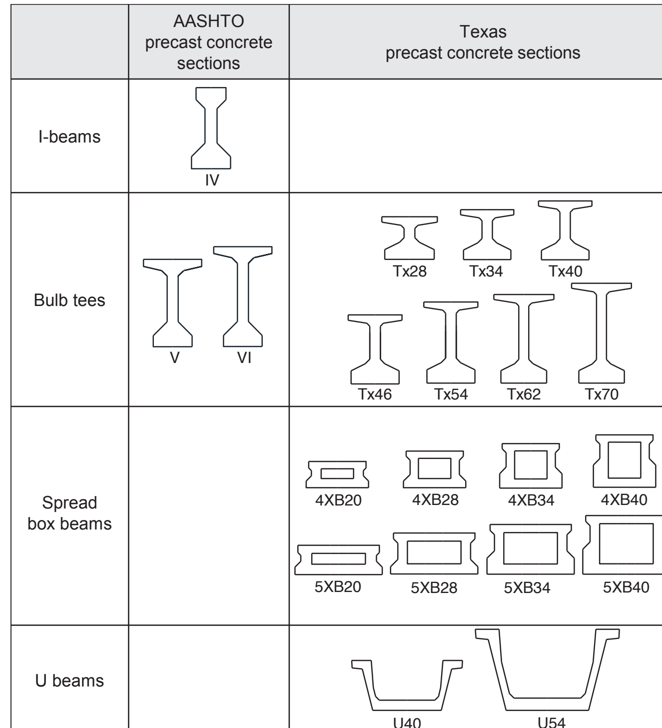

Figure 2. Cross sections investigated in the parametric study. Note: The last two-digit number in Texas precast concrete cross-section labels identifies the depth of the cross section in inches. The first digit in the spread box beams identifies the width in feet. 1 ft = 0.305 m; 1 in. = 25.4 mm.

girder cross sections, span lengths, concrete release strengths, girder spacings, and the choice between harped and straight strands.

Figure 2 shows the precast concrete cross sections investigated in this study. Twenty cross-section types were investigated, including AASHTO I-beams,[11] Texas bulb-tee girders (Tx),[14] AASHTO bulb-tee girders,[11] Texas spread box beams (XB),[15–18] and Texas U beams (U).[19] Three concrete release strengths of 5.5, 7.5, and 10 ksi (38, 52, and 69 MPa) were considered. The majority of cross sections considered were Texas precast concrete sections. In Texas, due to durability concerns, the compressive strength of concrete at release is generally limited to 5.5 ksi. However, to evaluate the potential benefits of increasing the release strength, values of 7.5 and 10 ksi were also studied. The effect of using a transverse girder spacing of 6 through 16 ft (1.8 through 4.9 m) was considered within the bridge configuration. To evaluate the role of harping in the ability to benefit from 0.7 in. (18 mm) diameter strands and therefore assess the need for upgrading the hold-down devices, I-girders and bulb-tee girders were designed both in straight and harped strand configurations. The combination of select designed parameters resulted in 10,320 cases, which required a versatile parametric study tool that could quickly generate thousands of designs and provide flexibility on input and output parameters.

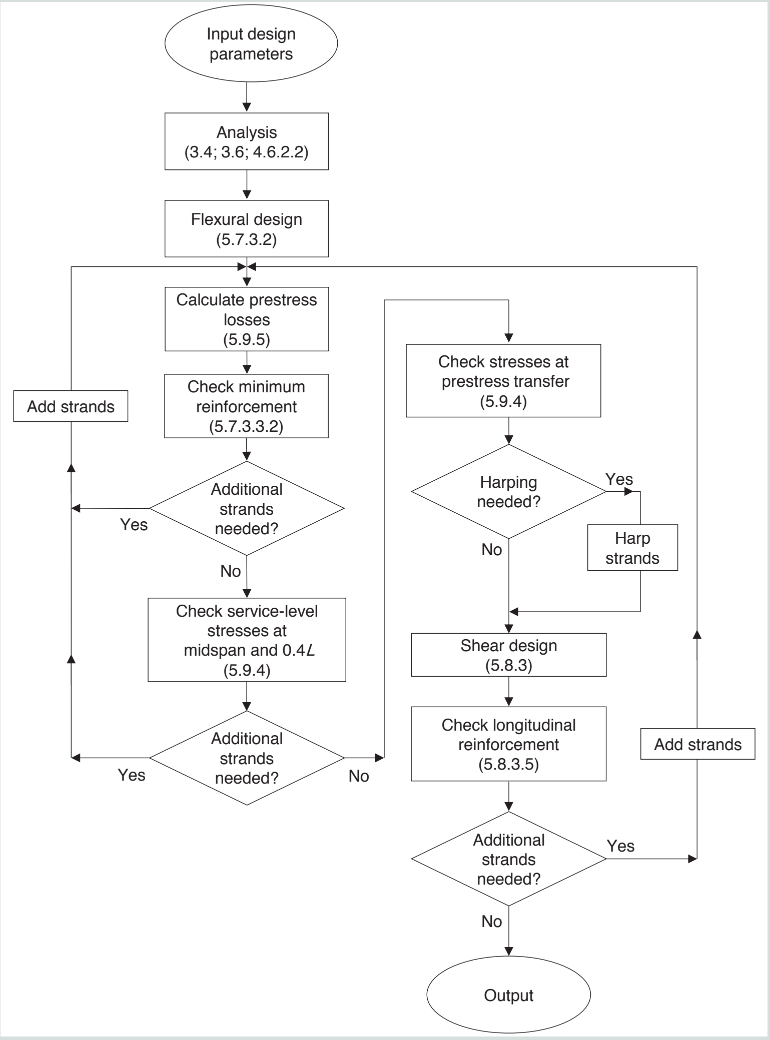

Figure 3. Design procedure for the parametric study tool. Note: L = girder length.

Parametric study tool

The designs were performed using a parametric study tool that employs a combination of spreadsheet formulas and macros. The tool was originally developed by Garber et al.[20,21] to investigate the effects of different prestress loss equations on the design of pretensioned concrete girders. To meet the requirements of the current study, this tool was modified to incorporate 0.7 in. (18 mm) diameter strands and reflect the most recent changes in design codes, including the 2016 interim revisions to the *AASHTO LRFD Bridge Design Specifications.*[22] Compared with bridge design software currently available, this parametric study tool provides greater control over input and output parameters, allows for procedures to be customized, and quickly generates numerous bridge designs in order to accelerate analyses.

Design procedure **Figure 3** provides an overview of the design procedure employed within the parametric analysis tool. In the flowchart presented, relevant articles from the AASHTO LRFD specifications[22] are provided. The design process starts with gathering the input parameters that define the design case. These input parameters include the bridge configuration (length, girder spacing, number of girders, interior or exterior girder classification, barrier base width, additional sustained dead load, and future overlay load), site conditions (relative humidity), cross-sectional properties of the precast concrete section (girder cross-section type, haunch thickness, and slab thickness), and assumptions for mechanical properties of the materials:

- for girder concrete: compressive strength at release f'_{ci}, compressive strength at 28 days f'_c, modulus of elasticity E_c, and unit weight w_c
- for slab concrete: f'_c, E_c, and w_c

- for prestressing strands: ultimate strength f_{pu}, jacking stress limit f_{pi}, yield strength f_{py}, modulus of elasticity E_p, and diameter d_b
- for mild steel reinforcement: yield strength f_y, modulus of elasticity E_s, and area

These parameters are manually inserted into the input sheets of the tool and updated as needed.

Using these input parameters, flexural demands on the girder in the final bridge configuration are determined based on dead and live loads that are applied to the bridge and the Strength I load combination from AASHTO LRFD specifications.[22] The number of strands needed at the midspan of the girder to satisfy this flexural demand is then determined.

Next, the minimum reinforcement requirements as well as tensile and compressive stress requirements for AASHTO LRFD specifications Service I and Service III limit states are checked and the quantity of prestressing strands is increased as needed. Once a satisfactory design that meets the flexural demands at ultimate and service conditions is achieved, the stresses at the time of release are calculated. The strands are then harped (deflected) as needed to satisfy the stress requirements at the time of prestress transfer. Finally, the girder is checked for shear strength at a section that is located d_v away from the support, where d_v is the effective shear depth.

The design procedure in the parametric study tool includes iterations to recalculate the relevant design parameters, such as section properties and prestress losses, whenever the number of strands is altered. Once a design is finalized, a full set of output parameters is generated. If a design meeting all requirements is not possible for a set of assumptions, the analysis tool outputs an error message that describes the requirement that cannot be satisfied.

Validation of the analysis tool To validate the parametric study tool, a set of comparative studies was conducted using bridge girder design software. A variety of Texas bulb-tee, Texas U and spread box, and AASHTO I and bulb-tee girders at different lengths and concrete compressive strengths were designed using the tool. The validation procedure included a comprehensive comparison between the design outputs as well as intermediate design parameters, such as stresses at the times of prestress transfer and deck placement, prestress losses, live load distribution factors, service-level stresses, ultimate bending moment, nominal flexural capacity, and minimum reinforcement requirements. The difference in the design parameters between the analysis tool and bridge girder design software was generally less than 5%, and the details are reported by Salazar.[23]

Parametric investigation

The parametric study tool was used to provide an inventory of design cases, which were then filtered as necessary to provide insight into the effects of using larger-diameter strands on different aspects of pretensioned concrete girder designs. The design cases were generated by changing the input parameters, most importantly the diameter of strands (0.5, 0.6, and 0.7 in. [13, 15, and 18 mm]), girder spacing, and span length, which was varied between 30 and 210 ft (9 and 64 m) at 5 ft (1.5 m) intervals.

For the purpose of this paper, all design cases were generated based on the assumption that 0.7 in. (18 mm) diameter strands can be used on a standard 2 × 2 in. (50 × 50 mm) grid without negatively affecting the serviceability or shear strength of the girders, and the end-region transverse reinforcement was assumed to sufficiently control the width of end-region cracks. These assumptions are investigated in detail in a comprehensive full-scale experimental program by the authors, which is reported by Salazar et al.,[24] Katz et al.,[25] and Kim et al.[26]

Table 1 provides a summary of the input parameters that were used for generating the design cases. An interior girder of a simply supported, single-span slab-on-girder bridge that contained six girders was considered. The 28-day compressive strengths of 10 and 4 ksi (69 and 28 MPa) were assumed for the concretes used in the girders and the slab, respectively. The compressive strength of concrete at the time of prestress transfer varied between 5.5 ksi (38 MPa) and 10 ksi. Release strengths greater than 10 ksi were not investigated because they may not represent a practical solution for the fabrication of precast concrete girders. For simplicity, the modulus of elasticity of concrete was assumed to be constant at the time of prestress transfer, equal to what is estimated for a compressive strength of 5.5 ksi from Eq. (C5.4.2.4-1) in the AASHTO LRFD specifications.[22]

For analysis purposes, the span length was assumed 1.5 ft (0.46 m) shorter than the girder length L. No haunch thickness was considered for this parametric investigation. The prestress losses were calculated according to the refined method (section 5.9.5.4) in the AASHTO LRFD specifications, assuming that the girders were subjected to prestress at an age of 0.8 days and the deck was constructed when the girder had an age of 120 days. The prestress level at the final conditions of the girders was calculated assuming a girder age of 100 years. The effects of deck shrinkage on prestress losses were neglected in the analysis.

All relevant loading combinations and stress limits according to the AASHTO LRFD specifications[22] were considered in design. In addition to the flexural design of the girders in ultimate conditions considering the live loads, the stresses were calculated at three stages: at the time of prestress transfer, at the time of deck placement, and under

Table 1. Properties used in the parametric study

Bridge configuration		Girder length L, ft	30 to 210
		Girder spacing, ft	6, 8, 10, and 12
		Number of girders	6
		Interior/exterior girder	Interior
		Additional sustained dead load, kip/ft	0.191
Site conditions		Relative humidity, %	60
Section properties		Girder cross-section type	Based on Fig. 2
		Slab thickness, in.	8.0
Material properties	Girder concrete	Compressive strength at prestress transfer f'_{ci}, ksi	5.5, 7.5, and 10.0
		Compressive strength at 28 days f'_c, ksi	10.0
		Concrete modulus of elasticity at prestress transfer E_{ci}, ksi	4270
		Concrete modulus of elasticity E_c, ksi	5760
		Concrete weight w_c, lb/ft³	150
	Slab concrete	Compressive strength of concrete at 28 days f'_c, ksi	4.0
		Concrete modulus of elasticity E_c, ksi	3640
		Concrete weight w_c, lb/ft³	150
	Prestressing strand	Ultimate strength of prestressing strand f_{pu}, ksi	270.0
		Jacking stress for prestressing strand f_{pj}, ksi	202.5
		Modulus of elasticity of prestressing strand E_p, ksi	29,000
		Diameter of the prestressing strand d_b, in.	0.5, 0.6, and 0.7
	Mild steel reinforcement	Yield strength of mild steel reinforcement f_y, ksi	60

Note: 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 kip/ft = 14.59 kN/m; 1 ksi = 6.895 MPa, 1 lb/ft³ = 16.03 kg/m³.

live loads in the final bridge configuration. These stresses were checked at three sections along the girder that were located at the transfer length of $60d_b$, at 40% of the girder length L, and at midspan. Moreover, the deflection of the girders under live loads was compared with the allowable limit of L/800, according to section 2.5.2.6.2 in the AASHTO LRFD specifications.

For the results presented in this paper, harping of the strands was assumed as the only method for controlling the stresses within the end region of the girders, which was applied as necessary to I-girders and bulb-tee girders. U and spread box beams were designed only with straight strands. No straight strands were assumed in the top flange of the girders.

Results and discussion

Within the following sections, the results of the parametric investigation are provided and discussed. These results are categorized to provide insight into the effects of using 0.7 in. (18 mm) diameter strands on steel quantity, maximum span capability, maximum attainable slenderness ratio for the superstructure, and maximum allowable spacing between the girders. Under each category, benefits obtained from using 0.7 in. strands are discussed and quantified in light of comparisons with results obtained for girders employing 0.6 in. (15 mm) diameter strands.

Steel quantity

Figures 4 and **5** present the number of required strands versus span length for 0.5, 0.6, and 0.7 in. (13, 15, and 18 mm) diameter strands in a variety of precast, pretensioned concrete cross sections. A transverse spacing of 8 ft (2.4 m) between the girders was assumed for generating the plots in these figures. The data points are in one of the three zones (5.5, 7.5, or 10 ksi [38, 52, and 69 MPa]) based on the compressive release strength required to reach each span length. The maximum span length before the live load

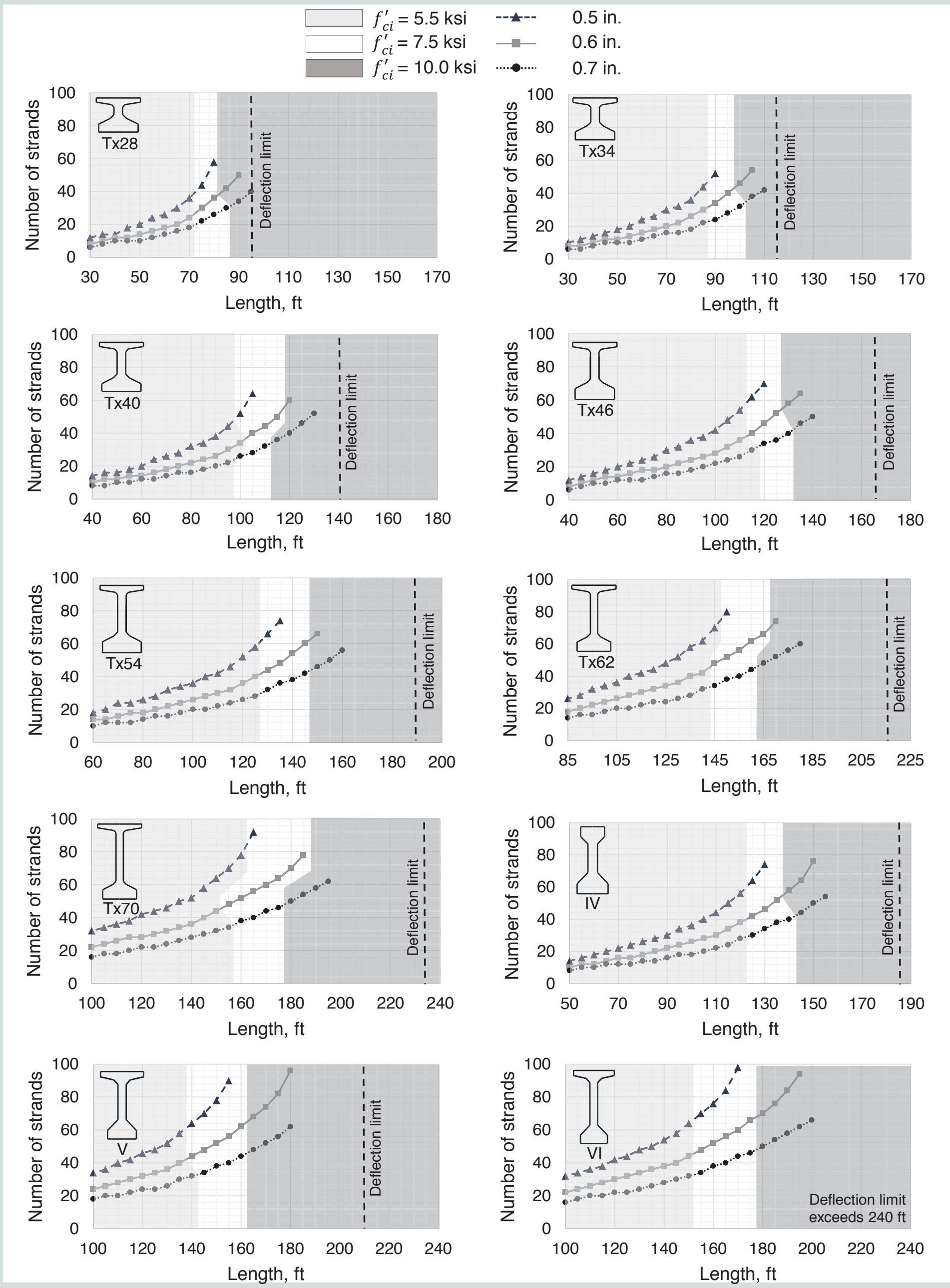

Figure 4. Number of strands versus span length for I-girders and bulb-tee girders with 0.5, 0.6, and 0.7 in. diameter strands. Note: f'_{ci} = compressive strength of concrete at prestress transfer. The last two-digit number in Tx girder labels identifies the depth of the cross section in inches. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

deflection exceeds the 1/800 limit is also shown in each plot as the "deflection limit." As visible in the figures, the deflection limit did not govern any of the design cases.

A considerable reduction in the number of strands due to the use of larger-diameter strands is evident in all plots in Fig. 4 and 5. This observation comes as no surprise because fewer large-diameter strands would be needed to provide the same area of prestressing steel. Up to 34 fewer strands could be used in AASHTO Type V girders when 0.7 in. (18 mm) diameter strands are used instead of 0.6 in. (15 mm) diameter strands (Fig. 4). This change, which corresponds to a 35% reduction, was the greatest savings in the number of strands in the entire set of design cases investigated. At the maximum span length that can be achieved with all strand diameters for each cross section L_{common}, the use of 0.7 in. strands results in a need for 10 to 16 fewer strands in Tx girders and 12 to 16 fewer strands in AASHTO I-sections compared with 0.6 in. strands. Similar observations regarding the saving in the number of strands can be made for U and spread box beams. When 0.7 in. strands are used instead of 0.6 in. strands, at the

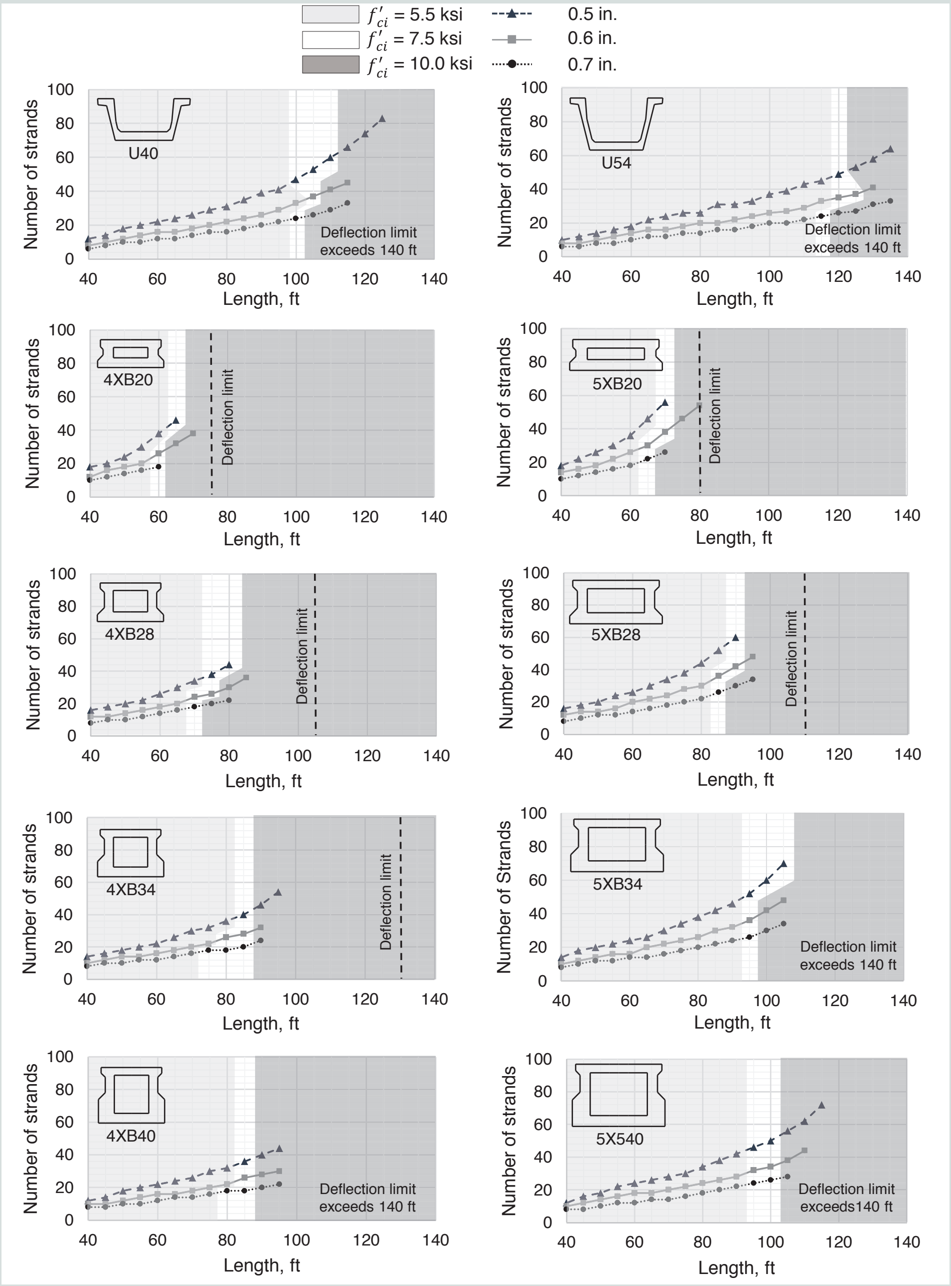

Figure 5. Number of strands versus span length for U and spread box beams with 0.5, 0.6, and 0.7 in. diameter strands. Note: The last two-digit number in each cross-section label identifies the depth of the cross section in inches. The first digit in the spread box beams identifies the width in feet. f'_{ci} = compressive strength of concrete at prestress transfer. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

maximum attainable span, 10 to 12 fewer strands will be needed in U beams and 8 to 14 fewer strands will be needed in spread box beams (Fig. 5).

Figures 6 and **7** show the reduction in steel quantity when 0.6 and 0.7 in. (15 and 18 mm) diameter strands are used instead of 0.5 in. (13 mm) diameter strands for I-girders and bulb-tee girders and for U and spread box beams, respectively. The comparisons presented in these figures are based on designs that were made at a transverse spacing of 8 ft (2.4 m) and a length of L_{common} for each cross section. The reduction in steel quantity in the figures is presented in two categories: the total weight of prestressing steel (shown on the left) and number of strands (shown on the right). The weight of steel is the primary indicator of material efficiency. However, the number of strands has a more noticeable effect on the physical demands of the fabrication process. Therefore, any reduction in the number of strands, regardless of the total weight of prestressing steel, will provide significant benefits to the cost effectiveness of the construction.

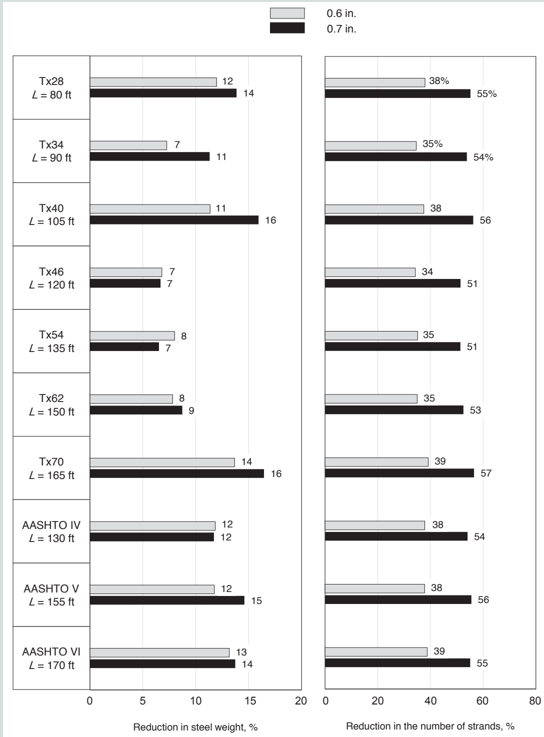

Figure 6. Percentage reduction in steel weight and number of strands for 0.6 and 0.7 in. diameter strands compared with 0.5 in. diameter strands within I-girders and bulb-tee girders. Note: The last two-digit number in Tx girder labels identifies the depth of the cross section in inches. *L* = girder length. 1 in. = 25.4 mm; 1 ft = 0.305 m.

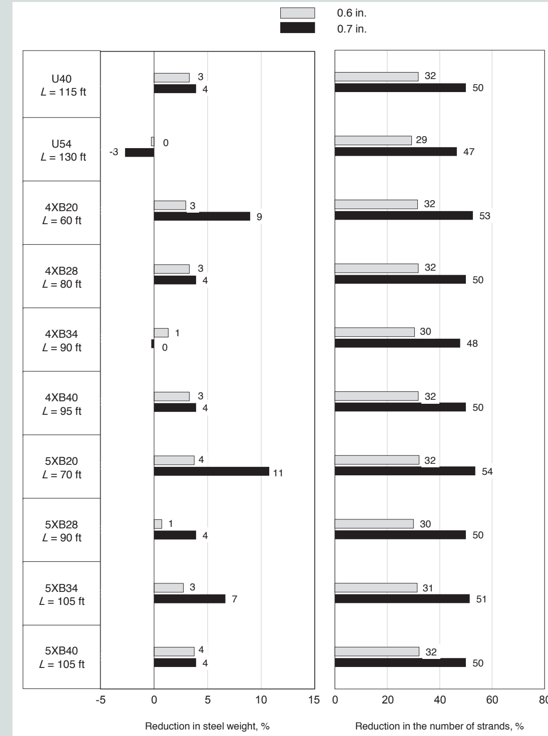

Figure 7. Percentage reduction in steel weight and number of strands for 0.6 and 0.7 in. diameter strands compared with 0.5 in. diameter strands within U beams and spread box beams. Note: *L* = girder length. The last two-digit number in each cross-section label identifies the depth of the cross section in inches. 1 in. = 25.4 mm; 1 ft = 0.305 m.

Figures 6 and 7 show that the use of 0.6 and 0.7 in. (15 and 18 mm) diameter strands results in up to a 16% reduction in the weight of prestressing steel compared with 0.5 in. (13 mm) diameter strands. Such a reduction is primarily due to the possibility of a greater concentration of steel near the bottom fiber and increased internal moment lever arm. However, using 0.7 in. strands provides no significant benefit in terms of steel weight compared with 0.6 in. strands. The maximum additional benefit from 0.7 in. strands compared with 0.6 in. strands was 5% (for Tx40 [1020 mm]) among I-girders and bulb-tee girders and 7% (for 5XB20 [510 mm]) among U and spread box beams. An opposite trend was observed for U54 (1370 mm), in which the weight of 0.6 and 0.7 in. strands exceeded that of 0.5 in. strands.

A relatively uniform reduction in the number of strands was observed within each category of cross sections (Fig. 6 and 7). In I-girders and bulb-tee girders, the use of 0.6 in. (15 mm) diameter strands instead of 0.5 in. (13 mm) diameter strands results in an average reduction of 34% to 39% in the number of strands. For 0.7 in. (18 mm) diameter strands compared with 0.5 in. strands, this reduction is 51% to 57%. For U and spread box beams, the reduction is 29% to 32% for 0.6 in. strands and 47% to 54% for 0.7 in. strands. The cross-sectional area of a 0.5 in. strand is 29% and 48% less than the cross-sectional areas of 0.6 and 0.7 in. strands, respectively. Therefore, the observed additional savings in the number of strands is associated with the improved flexural efficiency of the cross sections and a reduction in the required steel area.

For U and spread box beams, the reduction in the weight of steel and number of strands due to using larger-diameter strands was slightly smaller because the strand layout in these cross sections restricts how far the center of gravity of prestressing steel can be moved by concentrating a greater steel area near the bottom fiber. The maximum benefit from the use of 0.7 in. (18 mm) diameter strands instead of 0.5 in. (13 mm) diameter strands was in 5XB20 (508 mm), where an 11% reduction was observed in the weight of prestressing strands. Among I-girders and bulb-tee girders, Tx girders with a height between 46 and 62 in. (1170 and 1570 mm) benefitted the least from the use of larger-diameter strands. The use of 0.7 in. strands instead of 0.5 in. strands benefitted Tx70 (1780 mm) the most, both in terms of number of strands and weight of steel.

Maximum span capability

Figures 8 and **9** show the maximum span lengths for girders with 0.5, 0.6, and 0.7 in. (13, 15, and 18 mm) diameter

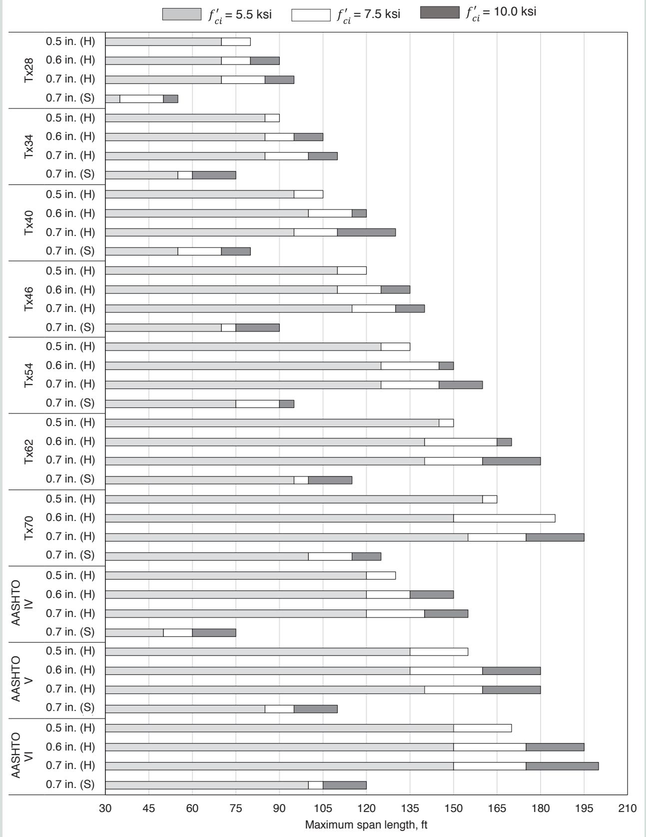

Figure 8. Maximum span lengths achieved for I-girders and bulb-tee girders with 0.5, 0.6, and 0.7 in. diameter strands. Note: The last two-digit number in Tx girder labels identifies the depth of the cross section in inches. f'_{ci} = compressive strength of concrete at prestress transfer; (H) = strands harped as needed; (S) = straight strands only. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

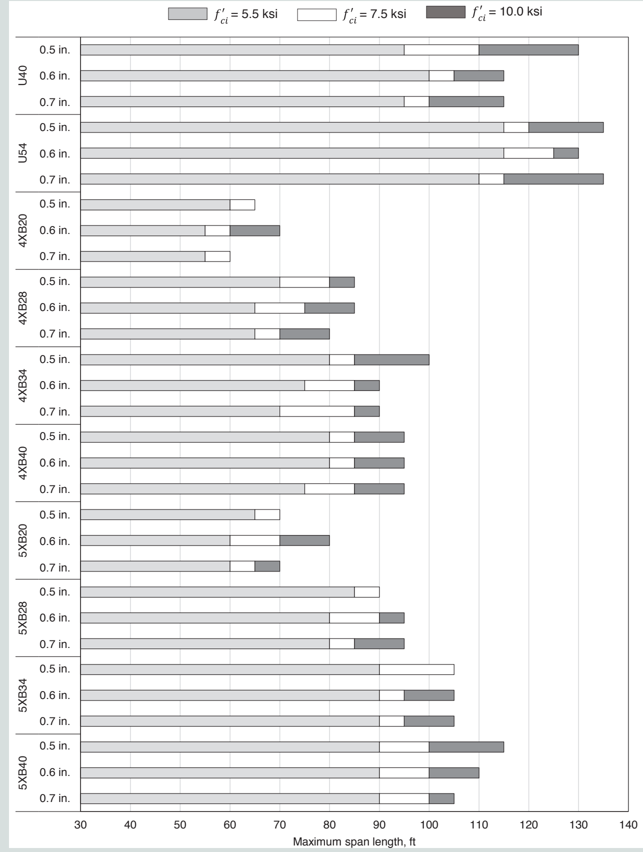

Figure 9. Maximum span lengths achieved for U beams and spread box beams with 0.5, 0.6, and 0.7 in. diameter strands. Note: The last two-digit number in each cross-section label identifies the depth of the cross section in inches. f'_{ci} = compressive strength of concrete at prestress transfer. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

strands fabricated with different concrete release strengths. The span lengths in these figures are primarily extracted from Fig. 4 and 5, in which a spacing of 8 ft (2.4 m) was assumed between the girders. In addition, Fig. 8 includes information on I-girders and bulb-tee girders with straight 0.7 in. strands to illustrate the importance of harping the strands in achieving greater span lengths. For U and spread box beams, only straight strands were considered. All span lengths reported in the figures have a resolution of 5 ft (1.5 m).

Figures 8 and 9 show that for each section, different span lengths could be achieved with different strand sizes. The two limits that governed the maximum span lengths were the maximum number of strands that could be accommodated in each girder cross section, and maximum stresses, either in final bridge configurations under live loads or at the time of prestress transfer. With 0.5 in. (13 mm) diameter strands, the maximum span lengths for all I-, bulb-tee, U, and spread box beams were governed by the number of strands that could be used within the girder cross section. The same situation applied to AASHTO bulb-tee girders and smaller Tx girders with 0.6 in. (15 mm) diameter strands. Concrete release strength was the governing factor for all girders with 0.7 in. (18 mm) diameter strands, as well as midsized to large Tx girders and U and spread box beams with 0.6 in. strands.

None of the combinations of strand sizes and cross-section types could reach the maximum span capability with a compressive release strength of 5.5 ksi (38 MPa). A release strength of 7.5 ksi (52 MPa) is needed to eliminate the release stresses from factors that govern the design of I-, bulb-tee, and small and midsized spread box beams with 0.5 in. (13 mm) diameter strands, Tx70 (1780 mm) girders with 0.6 in. (15 mm) diameter strands, and 4XB20 (510 mm) girders with 0.7 in. (18 mm) diameter strands. All other design cases, including almost all girders with 0.7 in. strands, require compressive release strengths greater than 7.5 ksi to be used efficiently.

A compressive release strength of 5.5 ksi (38 MPa) limits the span capability of almost all girders with 0.7 in. (18 mm) diameter strands to the same or smaller lengths as those with 0.5 or 0.6 in. (13 or 15 mm) diameter strands (Fig. 8). The only exceptions are Tx46 (1170 mm) and AASHTO Type V, for which a 5 ft (1.5 m) increase in the span length could be achieved by replacing 0.6 with 0.7 in. strands.

If the release strength is increased to 7.5 ksi (52 MPa), the span capability of I-girders and bulb-tee girders will increase for all design cases. The effects of such an increase in release strength are most visible in larger cross sections and larger-diameter strands, such as up to 35 ft (11 m) for Tx70 (1780 mm) with 0.6 in. (15 mm) diameter strands. However, even with this release strength, the maximum span length of girders with 0.7 in. (18 mm) diameter strands is only up to 5 ft (1.5 m) greater than that of girders with 0.6 in. strands.

A further increase in the release strength to 10 ksi (69 MPa) results in an increase in the span capability of most design cases, especially those with 0.7 in. (18 mm) diameter strands. As previously stated, if the release strength of 7.5 ksi (52 MPa) is provided, I-girders and bulb-tee girders with 0.5 in. (13 mm) strands will not be governed by release stresses. Therefore, increasing the release strength beyond 7.5 ksi does not improve the span capability of girders with 0.5 in. strands. For 0.6 in. (15 mm) and 0.7 in. diameter strands, however, increasing the release strength from 7.5 to 10 ksi increases the span capability by up to 25 ft (7.6 m) in some cases (for example, AASHTO Type VI).

If the release strength is increased to 10 ksi (69 MPa), I-girders and bulb-tee girders can benefit from an increase in their span capability when 0.6 or 0.7 in. (15 of 18 mm) diameter strands are used instead of 0.5 in. (13 mm) diameter strands. For example, Tx70 (1780 mm) benefits from a 30 ft (9.1 m) increase in its span capability with the use of 0.7 in. instead of 0.5 in. strands. Moreover, the use of 0.7 in. strands instead of 0.6 in. strands can result in an increase of up to 10 ft (3 m) in the span capability of I-girders and bulb-tee girders. This increase can be observed in Tx40 (1020 mm), Tx54 (1370 mm), Tx62 (1570 mm), and Tx70. However, because shipping limitations need to be considered for precast concrete elements in most applications, Tx54, Tx62, and Tx70 are unlikely to benefit from the 10 ft increase in their span capability. For other cross sections, a gain of 5 ft (1.5 m) can be observed in the span length when 0.7 in. strands are used instead of 0.6 in. strands.

Figure 8 also shows that controlling the end-region stresses through harping of the strands or other methods plays a major role in utilizing the larger-diameter strands. The span lengths of girders with straight 0.7 in. (18 mm) diameter strands are more limited, especially for AASHTO precast concrete cross sections. For a similar reason, assuming that the release strength is limited to 10 ksi (69 MPa), 0.7 in. strands do not provide any benefit to the span capability of U and spread box beams (Fig. 9).

Because the design for a majority of investigated U and spread box beams is governed by stresses at the time of prestress transfer, increasing the release strength can improve the span capability of these sections. For example, for U40 (1020 mm), an increase in the release strength from 7.5 to 10 ksi (52 to 69 MPa) results in a 35 ft (11 m) increase in the maximum span. However, the maximum span length of U and spread box beams with 0.7 in. (18 mm) diameter strands is not greater than those with 0.5 in. (13 mm) diameter strands for any of the release strengths considered. In cross sections such as 5XB20 (510 mm) and 5XB34 (860 mm), girders with 0.7 in. strands and a release strength of 10 ksi could reach the same span capability as those with 0.5 in. strands that are released at 7.5 ksi. Similar observations can be made for girders with 0.6 in. (15 mm) diameter strands, with the exception of 4XB20 (510 mm) and 5XB20, which re-

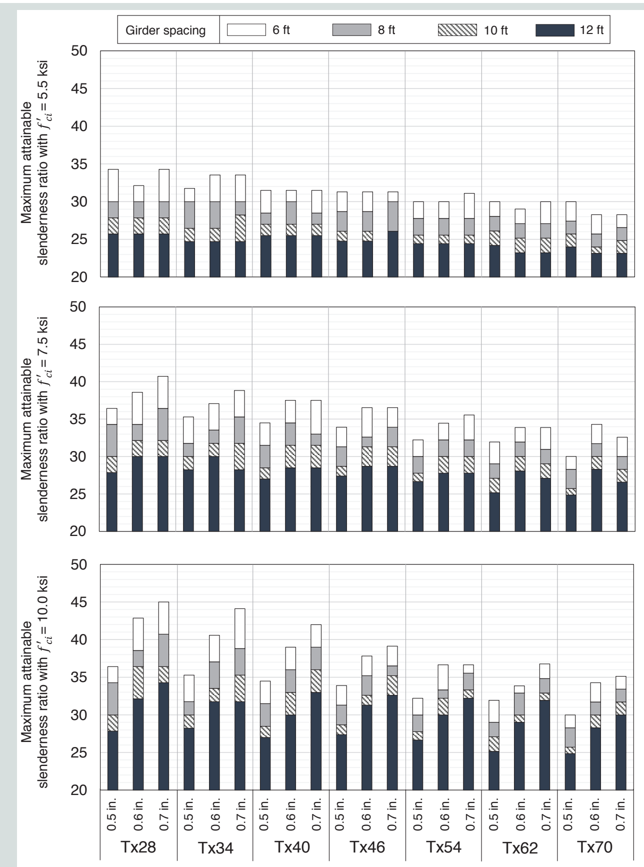

Figure 10. Maximum attainable slenderness ratio *MASR* for 0.5, 0.6, and 0.7 in. diameter strands in Tx girders. Note: The last two-digit number in Tx girder labels identifies the depth of the cross section in inches. f'_{ci} = compressive strength of concrete at prestress transfer. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

spectively gain 5 and 10 ft (1.5 and 3.0 m) compared with those with 0.5 in. strands.

Slenderness of the superstructure

Figure 10 shows the effects of using different diameters of strands on the slenderness of the superstructure. To summarize the results, the maximum attainable slenderness ratio *MASR*, which is defined as the maximum span length over the depth of the girder cross section, was obtained for different strand diameters and concrete release strengths. The spacing between girders was varied among 6, 8, 10, and 12 ft (1.8, 2.4, 3.0, and 3.7 m). For ease of discussion, only Tx girders are presented.

A comparison among the three plots in Fig. 10 shows that regardless of the strand diameter, *MASR* can be increased with an increase in the concrete release strength. However, the transition from 5.5 to 7.5 ksi (38 to 52 MPa) results in a greater gain in *MASR* compared with that from 7.5 to 10 ksi (69 MPa). When the release strength is increased from 5.5 ksi to 7.5 and 10 ksi, the maximum increase in *MASR* was approximately 20% and 30%, respectively.

With a release strength of 5.5 ksi (38 MPa), the *MASR* of most of the girders with larger-diameter strands does not exceed that of girders with 0.5 in. (13 mm) diameter strands, due to restrictive release conditions. However, girders with 0.7 in. (18 mm) diameter strands achieve equal or greater slenderness ratios than girders with 0.6 in. (15 mm) diameter strands.

By increasing the release strength to 7.5 ksi (52 MPa), the use of larger-diameter strands positively influences the *MASR* for all Tx girders. At a spacing of 6 ft (1.8 m), the use of 0.6 in. (15 mm) diameter strands increases the *MASR* to between 6% (for Tx34 [860 mm]) and 14% (for Tx70 [1780 mm]). Similar improvements are found for the use of 0.7 in. (18 mm) diameter strands, which increase the *MASR* to between 6% (for Tx62 [1570 mm]) and 12% (for Tx28 [710 mm]) compared with 0.5 in. (13 mm) diameter strands. At this release strength, the use of 0.7 in. strands results in a slight improvement in the slenderness ratio for Tx28, Tx34, and Tx54 compared with 0.6 in. strands. However, such an improvement cannot be observed for other Tx girders. The *MASR* for Tx70 girders with 0.7 in. strands is less than that of girders with 0.6 in. strands.

A further increase in release strength to 10 ksi (69 MPa) positively influences the *MASR* for all Tx girders. At this release strength, Tx28 (710 mm) girders benefit the most from using larger-diameter strands, with an improvement of 18% and 24% in *MASR* when 0.6 and 0.7 in. (15 and 18 mm) diameter strands, respectively, are used instead of 0.5 in. (13 mm) diameter strands. The use of 0.7 in. strands instead of 0.6 in. strands resulted in an increase in *MASR* for all Tx girders except Tx54 (1370 mm). However, increasing the diameter of strands from 0.5 to 0.6 in. results in greater improvement in *MASR* compared with changing from 0.6 to 0.7 in. strands. Among the design cases investigated, the ratio of *MASR* for 0.7 in. strands to that for 0.6 in. strands was the greatest for Tx62 (1570 mm) girders that were spaced at 6 ft (1.8 m). For this cross section, the use of 0.7 in. strands instead of 0.5 in. strands increases *MASR* by 15%, while the increase associated with the use of 0.6 in. strands was only 6%. If a more practical spacing of 8 ft (2.4 m) is considered, Tx40 (1020 mm) girders represent the greatest improvement in *MASR* (by 8%) when 0.7 in. strands are used instead of 0.6 in. strands.

Another important observation from Fig. 10 is how *MASR* was dependent on the girder size. For each release strength investigated, a declining trend was detected in *MASR* as the girder depth increased. In other words, the use of larger Tx girders results in less-slender superstructures. Moreover, the *MASR* of smaller Tx girders benefitted the most from the use of 0.7 in. (18 mm) diameter strands.

Girder spacing

Figure 11 shows the effects of using different strand diameters on the maximum allowable transverse spacing between I-girders and bulb-tee girders that are fabricated using different release strengths. To generate this figure, the girder spacing was varied from 6 to 16 ft (1.8 to 4.9 m) at 1 ft (0.3 m) increments, and the maximum spacing at which the design requirements could be satisfied was identified. To simplify the discussion, the investigation was made at a selected span for each cross section. The selected span, which is referred to as the "maximum practical span," is chosen as 85% of L_{common} from Fig. 4, regardless of the

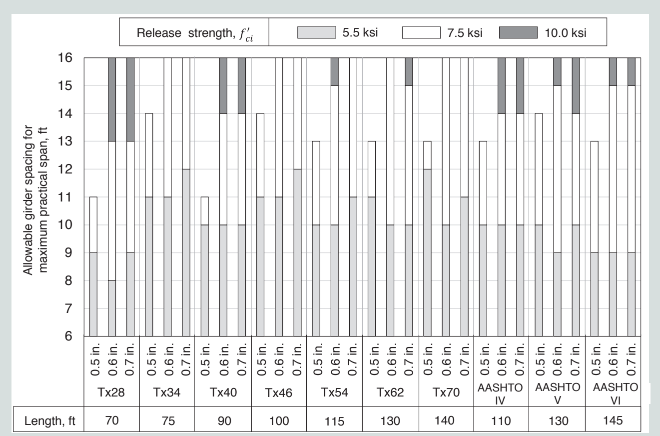

Figure 11. Allowable girder spacing at maximum practical spans for I-girders and bulb-tee girders employing 0.5, 0.6, and 0.7 in. diameter strands. Note: The last two-digit number in Tx girder labels identifies the depth of the cross section in inches. f'_{ci} = compressive strength of concrete at prestress transfer. 1 in. =25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

release strength. Recall that in determining L_{common}, the girders were assumed to be used at a spacing of 8 ft (2.4 m). The live load deflection limit was also considered but was not found to govern any of the design cases presented.

With a release strength of 5.5 ksi (38 MPa), most cross sections (except Tx28 [710 mm] and AASHTO Types V and VI) could be used at a girder spacing of 10 ft (3 m) at their maximum practical spans with all three strand diameters. In practice, the maximum girder spacing is usually limited to 10 ft due to costs associated with the slab that spans between girders. However, greater spacings were evaluated to gain insight into the potential benefits offered by larger-diameter strands.

Increasing the release strength from 5.5 to 7.5 ksi (38 to 52 MPa) results in a considerable increase in the allowable spacing for all girders, especially those with larger-diameter strands. With this release strength, all girders with 0.6 and 0.7 in. (15 and 18 mm) diameter strands could be used at a girder spacing of 13 ft (4.0 m) at their maximum practical spans. A maximum gain of 6 ft (1.8 m) in girder spacing takes place for Tx54 (1370 mm), Tx62 (1570 mm), Tx70 (1780 mm), and AASHTO Types V and VI girders that used 0.6 in. strands. A transverse spacing of up to 16 ft (4.9 m) is made possible for Tx34 (860 mm), Tx46 (1170 mm), and Tx70 for both 0.6 and 0.7 in. strands.

For girders that employ 0.5 in. (13 mm) diameter strands, increasing the release strength beyond 7.5 ksi (52 MPa) provides no additional benefit to the allowable transverse spacing. However, if the release strength is increased to 10 ksi (69 MPa), all girders with larger-diameter strands could potentially be used at greater transverse spacings, up to 16 ft (4.9 m). The increase is most noticeable for Tx28 (710 mm).

Figure 11 shows that the use of larger-diameter strands results in a noticeable increase in the allowable spacing between girders, especially when a release strength of 7.5 ksi (52 MPa) or greater is used. However, for girder spacings up to 16 ft (4.9 m), which were investigated, 0.7 in. (18 mm) diameter strands offered limited additional benefits compared with 0.6 in. (15 mm) diameter strands. The few cases in which 0.7 in. strands outperformed 0.6 in. strands by 1 ft (0.3 m) in terms of allowable spacing were Tx34 (860 mm), Tx46 (1170 mm), Tx54 (1370 mm), and Tx62 (1570 mm) with a release strength of 5.5 ksi (38 MPa) and Tx54 with a release strength of 7.5 ksi.

With a release strength of 7.5 ksi (52 MPa), all girders can be used at a transverse spacing of 11 ft (3.4 m), regardless of the strand diameter. Therefore, the use of 0.7 in. (18 mm) diameter strands offers benefits to girder spacing that are well beyond the practical limits and are therefore of limited real-world application.

Conclusion

A comprehensive parametric investigation was conducted to quantify the potential benefits obtained from using 0.7 in. (18 mm) diameter strands. This objective was achieved with a validated parametric study tool that is capable of designing a variety of precast, pretensioned concrete sections employing 0.5, 0.6, and 0.7 in. (13, 15, and 18 mm) diameter strands. Thousands of design cases were generated to determine the benefits of using 0.7 in. strands and the requirements for the efficient use of these larger-diameter strands.

The primary conclusions of the parametric study, which are categorized based on the perceived benefits attributed to the use of 0.7 in. (18 mm) diameter strands, are as follows:

- Steel quantity: The use of 0.7 in. (18 mm) diameter strands results in a considerable reduction in the number of strands. To achieve any span, the number of 0.7 in. strands needed is fewer than half the number of 0.5 in. (13 mm) diameter strands. The increased internal moment lever arm also results in a reduction of up to 16% in the weight of prestressing steel compared with 0.5 in. strands. However, the total weight of 0.7 in. strands would be comparable to that of 0.6 in. (15 mm) diameter strands. Benefits of 0.7 in. strands are most significant in larger I-girders and bulb-tee girders, where up to 16 fewer strands will be needed compared with 0.6 in. strands at practical span lengths. In U and spread box beams, the strand layout restricts how far the center of gravity of the strands can be moved. Therefore, the reduction in the number of strands does not correspond to a noticeable reduction in the total weight of prestressing steel in these sections.

- Span capability: I-girders and bulb-tee girders might benefit from a maximum gain of 10 ft (3 m) in span capability when 0.7 in. (18 mm) diameter strands are used instead of 0.6 in. (15 mm) diameter strands. However, this increase in span length requires a release strength of 10 ksi (69 MPa) or greater. In addition, harping or other methods for controlling end-region stresses will be needed. Unlike I-girders and bulb-tee girders, U and spread box beams that employ 0.7 in. strands do not reach greater span lengths compared with those with 0.5 in. (13 mm) diameter strands.

- Slenderness of superstructure: Benefits to the slenderness ratio with the use of 0.7 in. (18 mm) diameter strands were found to be dependent on the allowable release strength. For a release strength of 10 ksi (69 MPa), the use of 0.7 in. strands instead of 0.6 in. (15 mm) diameter strands resulted in an increase in the allowable slenderness ratio for the majority of Tx girders. However, increasing the diameter of strands from 0.5 in. (13 mm) to 0.6 in. results in greater improvement in the slenderness ratio compared with changing from 0.6 to 0.7 in. strands. Of the Tx girders considered, the smaller girder cross sections benefited the most from 0.7 in. strands.

- Allowable girder spacing: the majority of I-girders and bulb-tee girders investigated could be used at a girder spacing of up to 10 ft (3 m) with 0.5 in. (13 mm) diameter strands. The use of larger-diameter strands results in a noticeable increase in the allowable spacing between girders. However, for girder spacings up to 16 ft (4.9 m), 0.7 in. (18 mm) strands offer limited additional benefits compared with 0.6 in. (15 mm) diameter strands, and those benefits are observed at a spacing greater than the practical limits associated with the slab construction.

Other than reducing the number of strands, realizing the benefits associated with 0.7 in. (18 mm) diameter strands requires greater release strengths compared with what is currently used in practice. A release strength of 7.5 ksi (52 MPa) provides the opportunity to observe some benefits in terms of span length, girder spacing, and slenderness of superstructure from 0.7 in. strands compared with 0.6 in. (15 mm) diameter strands. A further increase in release strength to 10 ksi (69 MPa) results in noticeable advantages for 0.7 in. strands over 0.6 in. strands in terms of span capability (by 10 ft [3 m]) and slenderness of superstructure (by 8% at a transverse spacing of 8 ft [2.4 m]). Evaluating the practicality of such a release strength is beyond the scope of this paper. Unlike 0.6 and 0.7 in. strands, girders with 0.5 in. (13 mm) diameter strands do not benefit from release strengths greater than 7.5 ksi because their design will be governed by the maximum number of strands that can physically exist in the girder strand layout.

The investigation presented in this paper has primarily focused on cross sections that are used for precast concrete girders in Texas. Different conclusions may be reached if other cross sections are studied. Moreover, all conclusions in the paper are based on the assumption that 0.7 in. (18 mm) diameter strands can be used on a standard 2 × 2 in. (50 × 50 mm) grid without negatively affecting the serviceability or strength of pretensioned girders. The validity of this assumption for Tx girders is investigated in a full-scale experimental program by the authors and is reported in separate publications.[24–26]

Acknowledgments

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Notation

A_{ps} = cross-sectional area of the prestressing strand

d_b = diameter of the prestressing strand

d_v = effective shear depth

E_c = modulus of elasticity of concrete at 28 days

E_{ci} = modulus of elasticity of concrete at prestress transfer

E_p = modulus of elasticity of prestressing strands

E_s = modulus of elasticity of mild steel reinforcement

f_c' = compressive strength of concrete at 28 days

f_{ci}' = compressive strength of concrete at prestress transfer

f_{pi} = jacking stress for the prestressing strands

f_{pu} = ultimate strength of the prestressing strands

f_{py} = yield strength of the prestressing strands

f_y = yield strength of mild steel reinforcement

L = girder length

L_{common} = maximum span length that can be commonly achieved with 0.5, 0.6, and 0.7 in. (13, 15, and 18 mm) diameter strands for each cross-section type, assuming a transverse spacing of 8 ft (2.4 m) between the girders

$MASR$ = maximum attainable slenderness ratio

w_c = unit weight of concrete

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Abstract

This paper presents a parametric study on the benefits and limitations of using 0.7 in. (18 mm) diameter strands in precast, pretensioned concrete bridge girders. A validated parametric study tool was used to design a variety of Texas bulb-tee, U, and spread box beams and AASHTO I and bulb-tee girders with 0.5, 0.6, and 0.7 in. (13, 15, and 18 mm) diameter strands using different span lengths, concrete release strengths, and transverse spacings. The results were used to evaluate the effects of using 0.7 in. strands on the quantity of prestressing steel, span capability, attainable superstructure slenderness, and allowable spacing between girders. The most noticeable benefit of 0.7 in. strands over 0.6 in. strands was found to be a reduction of up to 35% in the number of strands. However, the difference in the total weight of prestressing steel was insignificant. Increasing the release strength of concrete, at least to 7.5 ksi (52 MPa), was found to be essential to observe benefits in design aspects other than the number of strands.

Keywords

Box beam, bridge, bulb tee, girder, parametric study, prestressing, pretensioning, 0.7 in. diameter strand, strand.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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