

Response of Pretensioned Concrete Beams to 0.7-in. Diameter Prestressing Strands with Experimental Verification

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ABSTRACT

During the past few years, 0.7-in. diameter, low-relaxation, seven-wire strands have been reported to be used in pretensioned beams of highway bridges. Use of the 0.7-in. diameter strands can provide significant savings in the number of strands compared to 0.5-in. and 0.6-in. diameter strands (75% and 50%, respectively). This reduction is a direct result of: (1) the significant increase in the precompression force produced by the 0.7-in. strands compared to the 0.5-in. and 0.6-in. diameter strands, (2) the ability to lower the centroid of the pretensioned strands that enhances the flexural strength of the pretensioned beams.

This paper presents the results of the analytical investigation conducted to examine the response of pretensioned concrete beams to 0.7-in. diameter strands. Non-linear finite element analysis, that recognizes the elasto-plastic behavior of concrete, was utilized in the analysis to investigate the following issues: (1) the effect of the strand spacing and concrete confinement on the transfer length, and (2) possible high stress concentration within the transfer length due to overlapping of the bond stresses of adjacent strands. The results of the analytical investigation are compared with available experimental data. The paper also presents a summary of the research conducted to investigate the behavior of pretensioned beams reinforced with the 0.7 in. strands.

Keywords: Bridge, girders, prestressed concrete, end zone cracking, 0.7-in. diameter strands, repair.

INTRODUCTION

The 0.7-in.-diameter strands were first used in external prestressing cables of the Narrows Bridge over the Swan River in Perth, Australia, which was opened to traffic in November 1959. Since then, several bridges around the world were built using 0.7-in.-diameter strands for unbonded, external post-tensioning. In the United States, only two manufacturers currently produce 0.7-in.-diameter strands, which are primarily used for mining applications¹.

Compared to the 0.5 in. and 0.6 in. diameter strands, the 0.7 in. diameter strands provide many advantages including:

- (1) Delivering significantly larger amount of pretensioning force compared to the 0.5-in. and 0.6-in. diameter strands, directly proportioned to the larger cross-sectional area (192% over 0.5-in. diameter strands and 135% over 0.6-in. diameter strands). This results in more economical girders with higher span-to-depth ratios, which can cover longer spans and/or used on wider spacing.
- (2) Reducing the number of strands, which in turn reduces the time and labor required for installation and pretensioning.
- (3) The ability of lowering the centroid of the pretensioned strands that enhances the flexural strength of pretensioned concrete girders.

These advantages were recognized in a parametric study that was conducted in the late 1990s¹. However, majority of the state DOTs are still reluctant to use the 0.7 in. diameter strand for the following reasons: (1) lack of experimental verification of the transfer and development length as stipulated by LRFD Specification², (2) lack of guidance on the recommended minimum spacing between strands; vertically and horizontally, and (3) lack of guidance on the amount of confinement required to protect the member end from cracking during prestress release.

In addition, there have been some production concerns raised by the precast concrete producer such as: (1) the need to modify the end plate assembly if the strand spacing is set to be greater than the 2-in. x 2-in. horizontal and vertical spacing layout that is typically used with 0.5 in. and 0.6-in. diameter strands, (2) the need to modify the hold-down devices to accommodate a higher level of uplift forces, (3) commercial availability of 0.7-in. diameter strands, and (4) handling the 0.7 in. strands may require modifying the equipment used to run the strands through the prestressing bed.

Objectives of this paper are: (1) provide information of the methodological approach of modeling pretensioned concrete members using the finite element method, (2) provide a brief summary on the parametric, analytical and experimental studies conducted using the 0.7 in. diameter strand, (3) study the effect of using the 0.7 in. diameter strand on the transfer length as stipulated by the LRFD Specification, (4) study the effect of the strand spacing on the imposed stresses at the core of the girder, and (5) study the effect of amount and spacing of the confinement reinforcement on the response of the girder during release.

LITERATURE REVIEW

Russell et al. performed one of the first parametric studies of optimized sections for high-performance-concrete (HPC) girders¹. In spite of unavailability of 0.7 in. diameter strands in the U.S. market at the time of the study, Russell et al. showed that the use of 0.7 in. diameter strands in combination with 10,000 psi concrete can result in the longest and most economical precast girders in comparison with the similar sections pretensioned with 0.5 in. and 0.6 in. diameter strands.

Morcous et al. conducted extensive experimental studies of the use of 0.7 in. diameter strands at the University of Nebraska-Lincoln³. One of the objectives of this research was to show that 0.7 in. diameter strands could be spaced at 2x2 in. horizontal and vertical grids without detrimental effects on the members. The 2x2 in. layout is similar to practice of pretensioning using 0.5 in. and 0.6-in. diameter strands. Therefore, if similar spacing can be used for 0.7 in. diameter strands, fabricators will be more willing to use 0.7 in. diameter strands without the need for costly retooling and modifications of the casting beds and abutments. In addition, the study showed that the measured transfer and development lengths of 0.7-in. diameter strands were below the corresponding recommendations by the AASHTO LRFD Design Specifications². The study concluded that the confinement reinforcement recommended by AASHTO LRFD should be considered as the minimum while additional confinement is recommended for enhancement of member ductility.

Based on the study that was conducted by Morcous et al., the Nebraska Department of Roads (NDOR) decided to use the 0.7-in. diameter strands in the Pacific Street project. The Pacific Street project included total of twenty 98'-4" long NU 900 girders. Due to the lack of previous data related to the use of 0.7-in. diameter strands as pretensioning elements, full-scale testing was performed prior to the production of the girders in order to ensure that the potential cracks at the time of release were similar to the usual end zone cracking of the pretensioned girders. Based on the full-scale test results, it was eventually decided that the end zone design and details recommended by the AASHTO LRFD Bridge Specifications were adequate for the purposes of the project. The main challenges of the production of the corresponding girders were the market availability of 0.7-in. diameter strands at the time and the need for larger hold-down devices^{4,5}.

Similar studies at the University of Tennessee-Knoxville examined AASHTO Bulb-Tee girders pretensioned with 0.7-in. diameter strands⁶. While the strands were spaced at 2 in. on center (both horizontally and vertically), the analytical and experimental results reported no cracking due to closer spacing of the strands. The study concluded that since 0.7-in. diameter strands generally were observed to have shorter transfer length compared with smaller diameter strands, larger splitting stresses were anticipated within the end zone of the member.

Akhnoukh also conducted a series of parametric studies with experimental tests on mono-strand prisms concentrically pretensioned using one 0.7-in. diameter strand⁷. One of the objectives of Akhnoukh's research was to determine an optimized transfer length for 0.7-in. diameter strands. Additionally, Akhnoukh investigated the effect of confinement reinforcement on the transfer length of the specimens.

EXPERIMENTAL DATA USED FOR CALIBRATION OF THE NUMERICAL MODEL

The experimental results reported by Akhnouk⁷ were utilized to calibrate the numerical model used in this research. The experimental program included fabrication and testing of 7-in. x 7-in. rectangular concrete beams, 8-ft long (each) with compressive strength of $f'_{ci} = 3,000 \text{ psi}$ at time of release. Each specimen was concentrically pretensioned using one 0.7-in. diameter low-relaxation seven-wire strand. The strand stress immediately prior to release was 202.5 ksi. Four classes of specimens were created using different spacing of the No. 3 confinement reinforcement, as shown in Table 1

Table 1. Characteristic properties of the specimens used for calibration of the numerical model

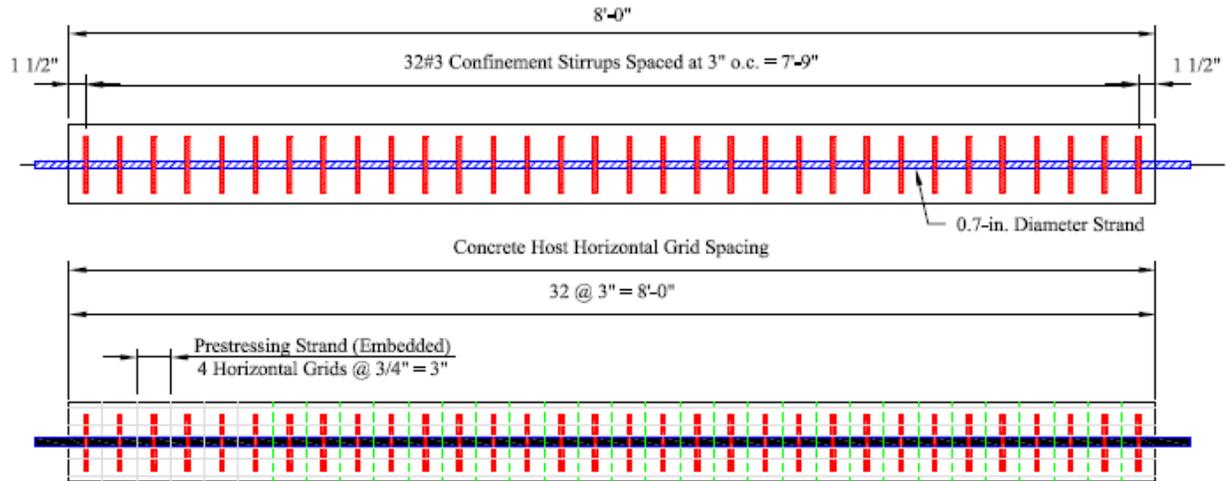
Specimen	Geometric Properties	Confinement	
		Reinforcement	Spacing
1-L8-3	7-in. x 7-in. x 8-ft (long)	No.3 Close Stirrup	3 in. on center
1-L8-6	7-in. x 7-in. x 8-ft (long)	No.3 Close Stirrup	6 in. on center
1-L8-9	7-in. x 7-in. x 8-ft (long)	No.3 Close Stirrup	9 in. on center
1-L8-12	7-in. x 7-in. x 8-ft (long)	No.3 Close Stirrup	12 in. on center

Once the response of the analytical models are verified against the experimental results, the mono-strand finite element models are then expanded to include nine 0.7-in. diameter strands hosted within prisms with larger cross-sectional areas to further evaluate the effects of strand groups and spacing on the transfer length.

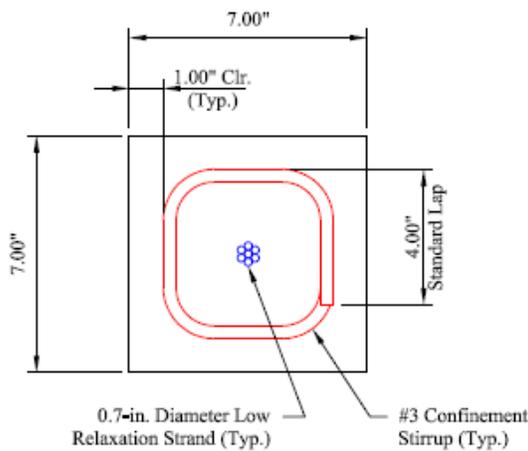
NUMERICAL SIMULATION OF MONO-STRAND SPECIMENS

Four classes of finite element models are constructed to correspond to the test specimens indicated in Table 1. Fig. 1 shows a typical analytical specimen with #3 confinement rebar spaced at 3-in. on center.

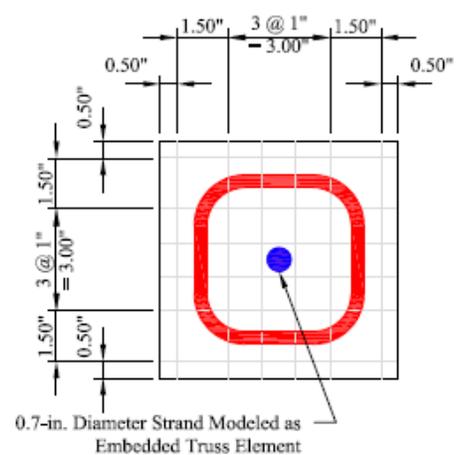
The finite element (FE) models are constructed using ABAQUS⁸. The nonlinear simulation of pretensioning is performed based on two different techniques: i) extrusion and ii) embedment.



ELEVATION



CROSS SECTION



CROSS SECTION

Fig. 1. A typical analytical mono-strand specimen with #3 confinement rebar at 3-in. spacing

The extrusion technique is based on modeling the interface between strands and concrete using friction contact formulations. This is facilitated by modeling the strands within an extruded concrete matrix as solid elements (e.g., 8-node elements) with common boundary surfaces. The extruded model requires a contact surface to accurately represent the interaction between concrete and strands. Based on the examinations conducted by the authors, it was decided that the built-in features in ABAQUS could adequately facilitate such simulations while requiring further calibrations. The contact surface includes many parameters that can be adjusted to calibrate the FE model, such as friction, slippage, pressure dependency and over-closure⁹. Fig. 2 shows a typical finite element model with one extruded 0.7-in. diameter strand and the embedded confinement rebar.

When extruded, strands are modeled as solid elements which are constrained with the host (concrete) through friction-based contact formulation which allows for slippage. The extruded models are further subdivided to the following two groups:

- Group 1 (*Slip_Max*): Minimum coefficient of contact friction $\mu_f = 0.7$ at the interface between the strand and concrete host, resulting in maximum slippage of strand upon release of pretensioning
- Group 2 (*Slip_Min*): Minimum coefficient of contact friction $\mu_f = 1.4$ at the interface between the strand and concrete host, resulting in minimum slippage of strand upon release of pretensioning

No.3 closed stirrup ties are modeled as embedded beam elements. Since the embedment technique constrains the translational degrees of freedom of the ties with the host element (concrete), there is no need to model the lap details to account for development length. Instead, development length of rebar is accounted for through numerical simulation of translational constraints.

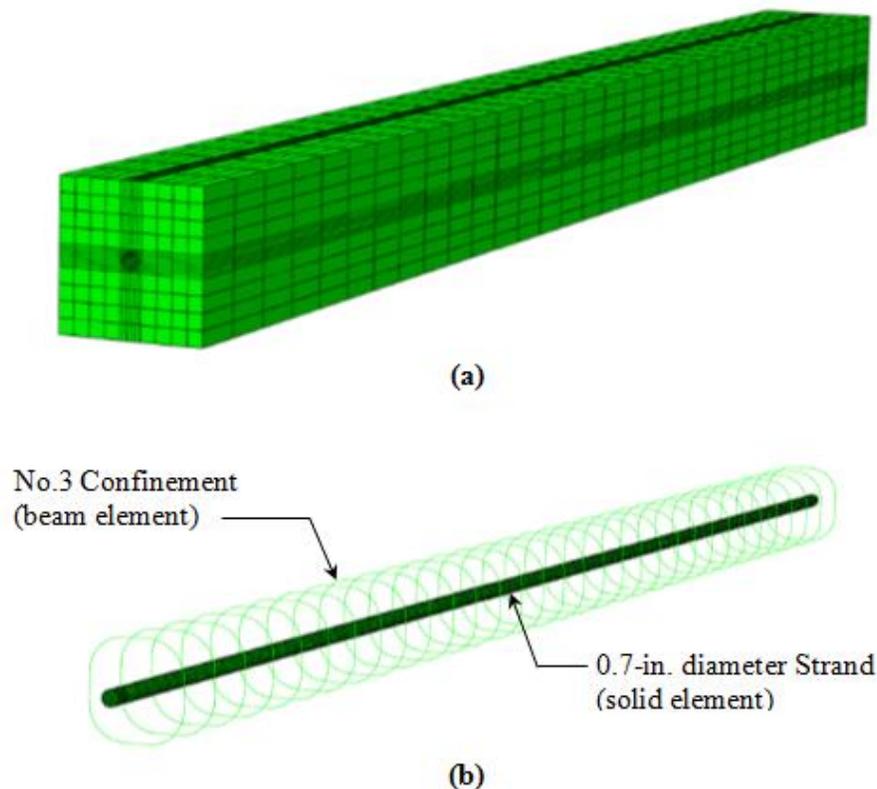


Fig. 2. Typical finite element model with one extruded pretensioned strand and embedded ties: (a) Concrete beam modeled as continuum elements, and (b) strands and ties modeled as solid and beam elements, respectively

Embedment, on the other hand, is another powerful numerical technique, which enables one or more elements to be embedded inside a host element. One of the most significant advantages of the embedment technique is the fact that it does not require modeling of contact surfaces, and therefore, eliminates the numerically expensive iterations associated with contact formulations⁹. An embedded element needs to be geometrically confined within the host element. The degrees of freedom at the nodes of the embedded element will be eliminated and the nodes will become “embedded nodes” while constrained to the interpolated values of the corresponding degrees of freedom of the host element. Fig. 3 shows a typical finite element model with one extruded 0.7-in. diameter strand and the embedded confinement rebar.

References 9 and 10 provide more details regarding theoretical basis as well as the practical applications of the extrusion and embedment techniques.

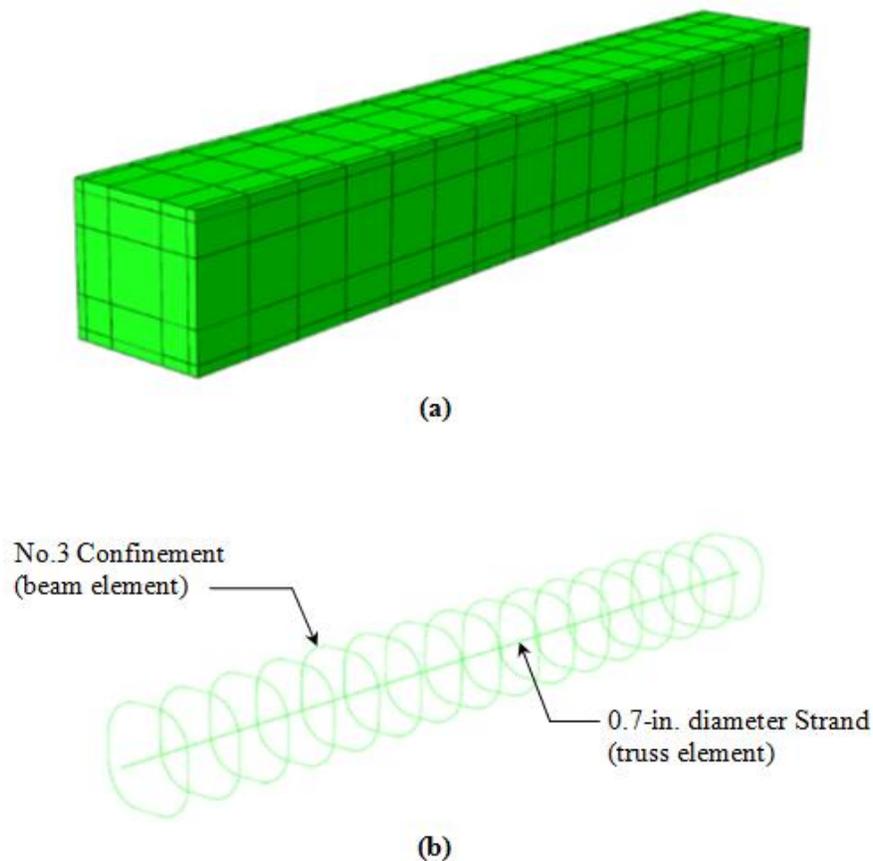


Fig. 3. Typical finite element model with one embedded pretensioned strand and embedded ties: (a) Concrete beam modeled as continuum elements, and (b) strands and ties modeled as truss and beam elements, respectively

When embedded, strands are modeled as truss elements slaved to the translational degrees of freedom of the solid host. The pretensioning mechanism (including transfer length) for the

embedded models is controlled by input parameters. Therefore, the pretensioning load path is pre-determined, calibrated, and then applied to the model based on the available experimental data. Fig. 4 shows the simulated transfer length based on the experimental data for the finite element models with a single embedded strand and No.3 confinement reinforcement spaced at 3 in., 6 in., 9 in. and 12 in., respectively. In addition, Fig. 4 shows the linear transfer length based on AASHTO LRFD² as assumed in current state of practice in the United States.

Fig. 4 shows that good correlation was obtained between the experimental results reported by Akhnouk⁷ for all the specimens except the specimens made with confinement spacing of 12 in. (Specimens 1-L8-12). Therefore, the test data obtained from this class of specimens are ignored for the purposes of this paper.

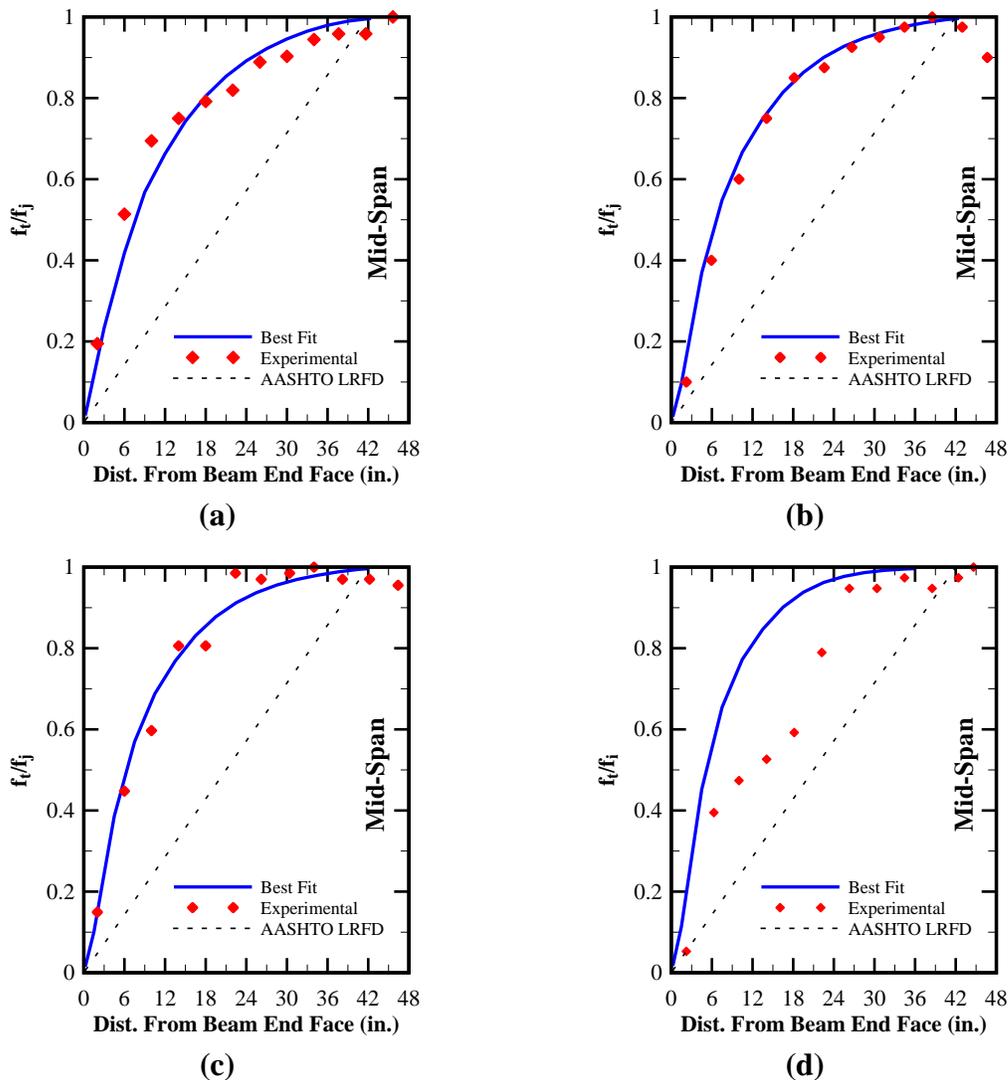


Fig. 4. Transfer length simulation for the finite element models with one 0.7-in. diameter embedded strand and #3 confinement rebar spaced at: (a) 3 in., (b) 6 in., (c) 9 in., and (d) 12 in. on center (See Ref. 7 for details of the experimental data)

VERIFICATION OF THE FE MODEL

Fig. 5 through Fig. 7 show the comparison of the analytical results obtained by the embedded and extruded finite element models 1-8L-3, 1-8L-6 and 1-8L-9, respectively, versus the experimental data. The normalized axial strains correspond to the response of the concrete prism immediately after the release of pretensioning and based on the transfer length established between the released strand and the concrete host. The results indicate that the assumption of linear stress (strain) path as assumed in the current practice underestimates the actual transfer length.

The parametric study showed that: (1) direct slippage of strand-over-concrete using the friction simulation provides an acceptable approximation of the pretensioning mechanism, including the transfer length phenomenon, (2) friction coefficients of 0.70 and 1.4 , in combination with Poisson’s effect appear to adequately provide lower and upper bound interface interactions between the strands and concrete host immediately after the release of pretensioning, and (3) the variation of axial stresses in the strands along the transfer length zone is found to be of nonlinear (parabolic) nature rather than the linear approximation recommended by the codes and guidelines used in current practice.

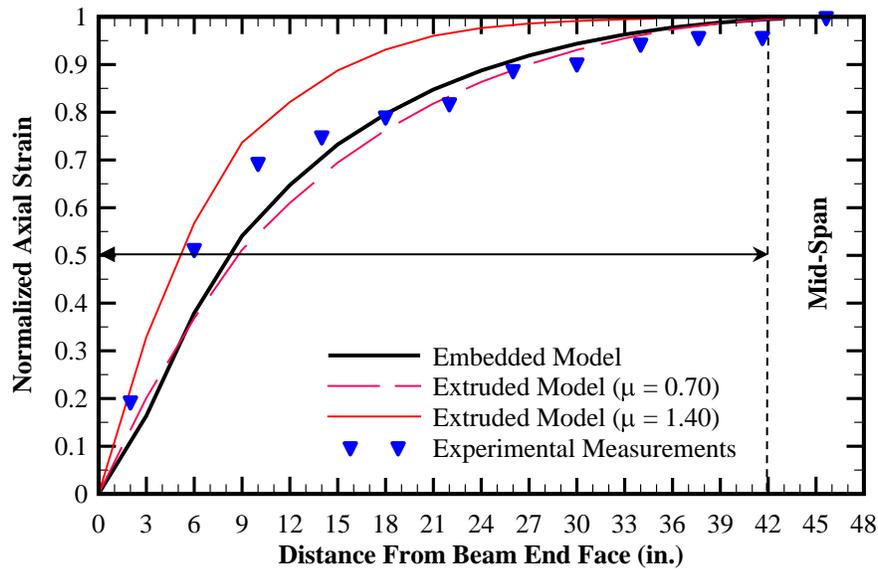


Fig. 5. Experimental measurements (strains) versus the mono-strand finite element model confined with No.3 close stirrups spaced at 3 in. on center (Specimen 1-8L-3)

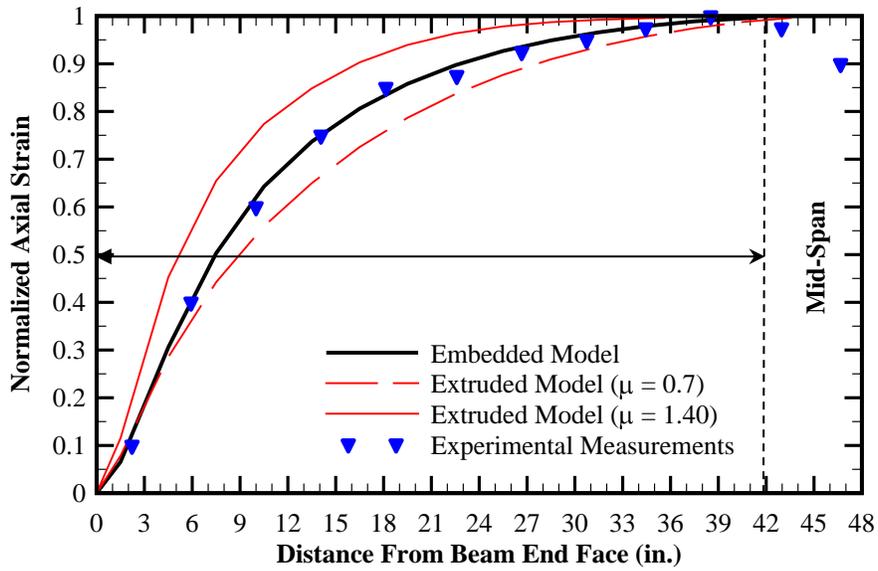


Fig. 6. Experimental measurements (strains) versus the mono-strand finite element model confined with No.3 close stirrups spaced at 6 in. on center (Specimen 1-8L-6)

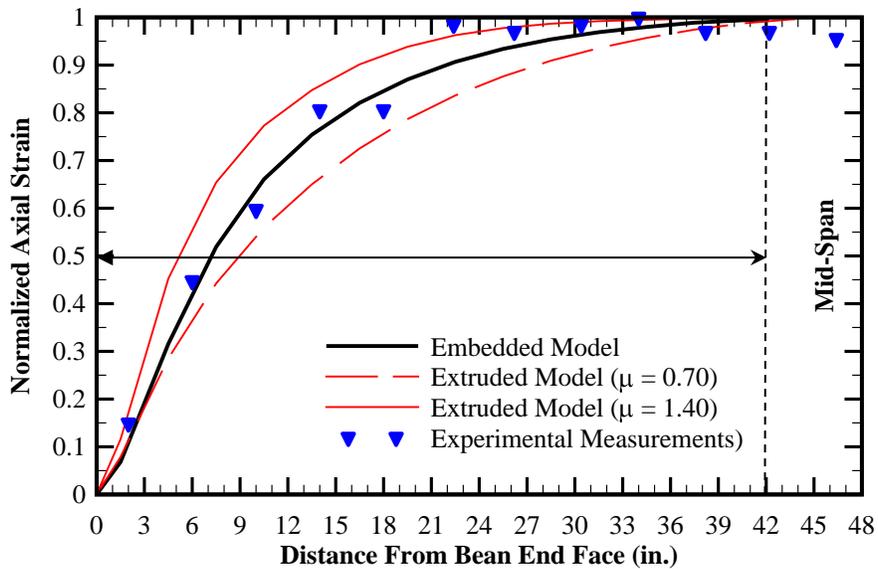


Fig. 7. Experimental measurements (strains) versus the mono-strand finite element model confined with No.3 close stirrups spaced at 9 in. on center (Specimen 1-8L-9)

As shown in Fig. 8, the analytical results indicate that the finite element models are sensitive to the effect of the confinement on the transfer length although such effects are not significant. This is also consistent with the experimental findings by Akhnoukh⁷.

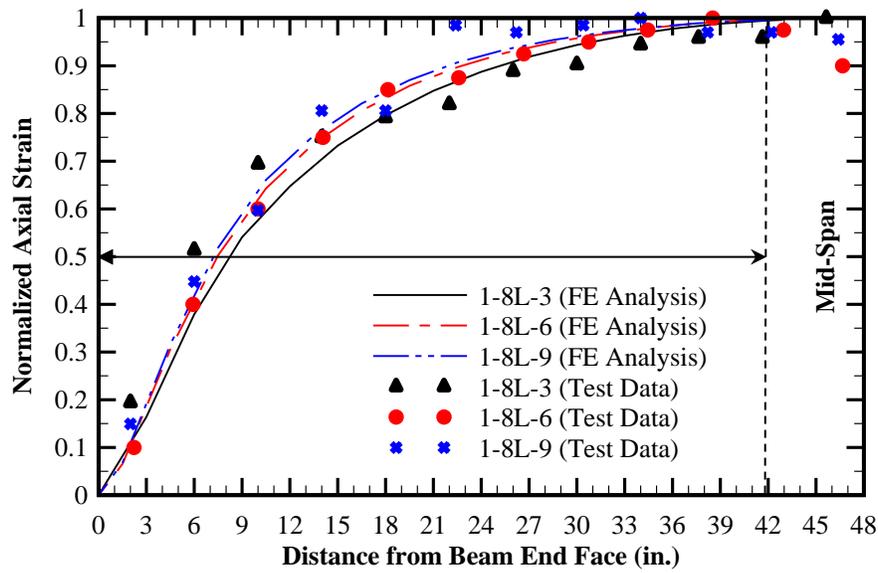


Fig. 8. Effect of confinement on transfer length (results of mono-strand finite element models with embedded strands versus test data)

FE SIMULATION OF SPECIMENS WITH NINE STRANDS

In order to study the effect of overlapping stresses created by adjacent strands, the authors examined a concrete prism that hosts 9 strands. The finite element (FE) models were based on 11-in. x 11-in. concrete prisms with compressive strength of $f'_{ci} = 8,000 \text{ psi}$ at the time of release and 28-day compressive strength of $f'_c = 10,000 \text{ psi}$. The prism is 20 ft long hosting nine 0.70-in. diameter low-relaxation strands modeled as solid elements (extrusion technique). The strands are symmetrically located around the centroid of the members in both horizontal and vertical grid spacing.

Two classes of finite element models with nine concentrically positioned 0.7-in. diameter low-relaxation strands are developed with the following variations of the strands spacing:

- Class I - The strands are spaced at four times the strand diameter in accordance with ACI318¹¹ requirement of minimum spacing of strands (2.8 in. for 0.7-in. diameter strands)
- Class II - The strands are spaced at 2.0 in. on center in conformance with the current standards of fabrication for pretensioned members with 0.6-in. diameter strands

Each class was further subdivided into two levels of contact friction at the interface between the strands and the concrete host as follows:

- Upper bound slippage at lowest contact friction coefficient of $\mu_f = 0.70$

- Lower bound slippage at highest contact friction coefficient of $\mu_f = 1.40$

In addition, the finite element models were investigated for the effect of the confinement reinforcement on the response of the specimens to the release of pretensioning. Thus, the response of the models to the same magnitude of pretensioning (jacking stress of 202.5 ksi) is evaluated when the specimens are confined with No.3 closed stirrups (modeled as embedded beam elements) spaced at 3 in., 6 in., 9 in. and 12 in. on center as well as when no confinement is present. **Table 2** gives the basic properties of finite element models. **Fig. 9** shows the details of a typical Class I finite element model with No.3 confinement closed stirrups spaced at 3 in. **Error! Reference source not found.** shows the details of a typical Class II finite element model with No.3 confinement closed stirrups spaced at 3 in.

Table 2. Log of Class I finite element models with nine extruded strands

Class	Model I.D.*	Strand spacing	Confinement	μ_f
I	S280-U070-C0	2.80 in.	Zero	0.70
	S280-U140-C0			1.4
II	S200-U070-C0	2.00 in.		0.70
	S200-U140-C0			1.4
I	S280-U070-C3	2.80 in.	No.3 @ 3 in.	0.70
	S280-U140-C3			1.4
II	S200-U070-C0	2.00 in.		0.70
	S200-U140-C0			1.4
I	S280-U070-C6	2.80 in.	No.3 @ 6 in.	0.70
	S280-U140-C6			1.4
II	S200-U070-C0	2.00 in.		0.70
	S200-U140-C0			1.4
I	S280-U070-C9	2.80 in.	No.3 @ 9 in.	0.70
	S280-U140-C9			1.4
II	S200-U070-C0	2.00 in.		0.70
	S200-U140-C0			1.4
I	S280-U070-C12	2.80 in.	No.3 @ 12 in.	0.70
	S280-U140-C12			1.4
II	S200-U070-C0	2.00 in.		0.70
	S200-U140-C0			1.4

* All models are 11-in. x 11-in. x 20-ft (long)

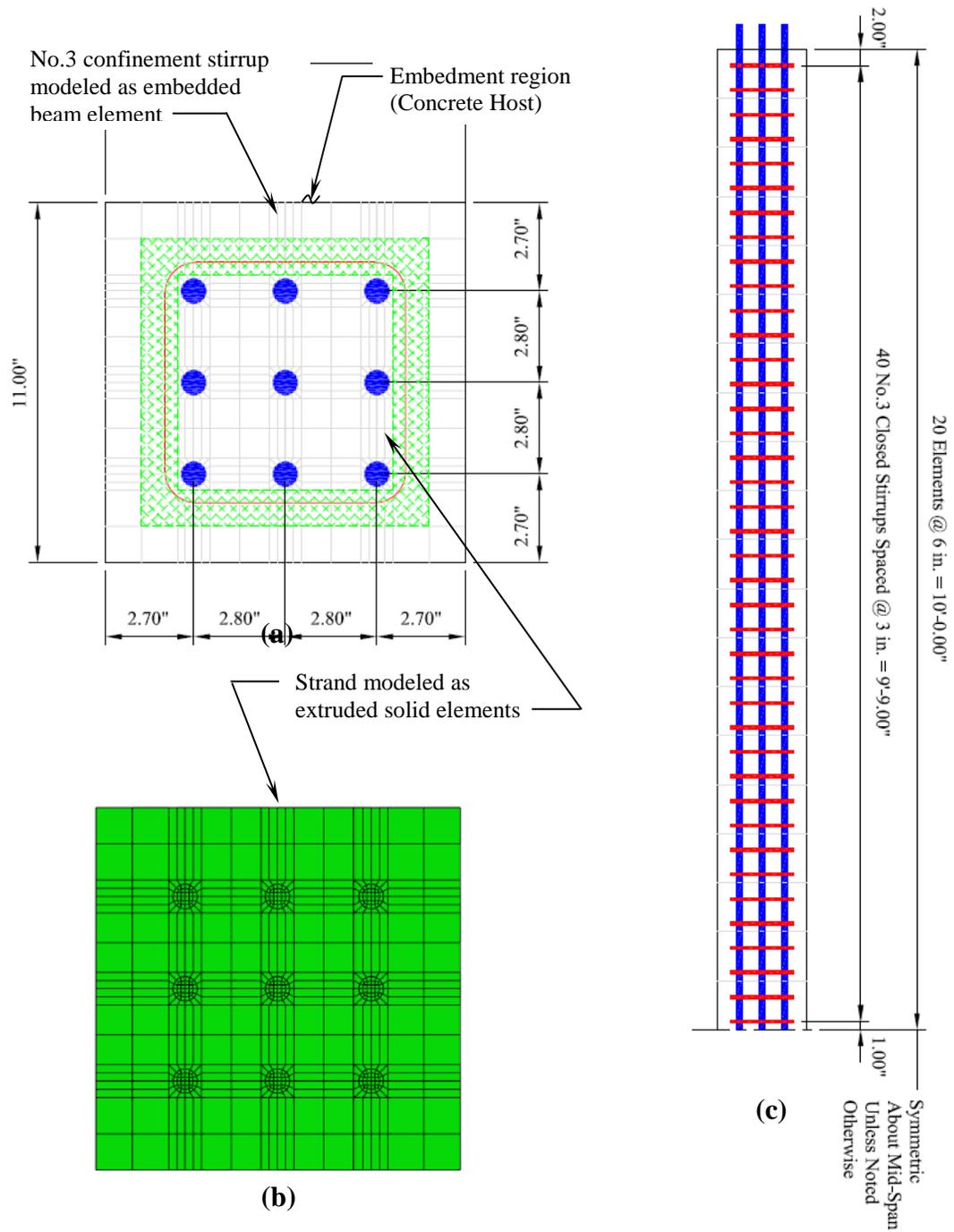


Fig. 9. Details of Class I [S280-U070-C3; S280-U140-C3] finite element models: (a) Typical cross section, (b) Finite element simulation, and (c) Layout of confinement reinforcement (No.3 closed stirrups spaced at 3 in. on center)

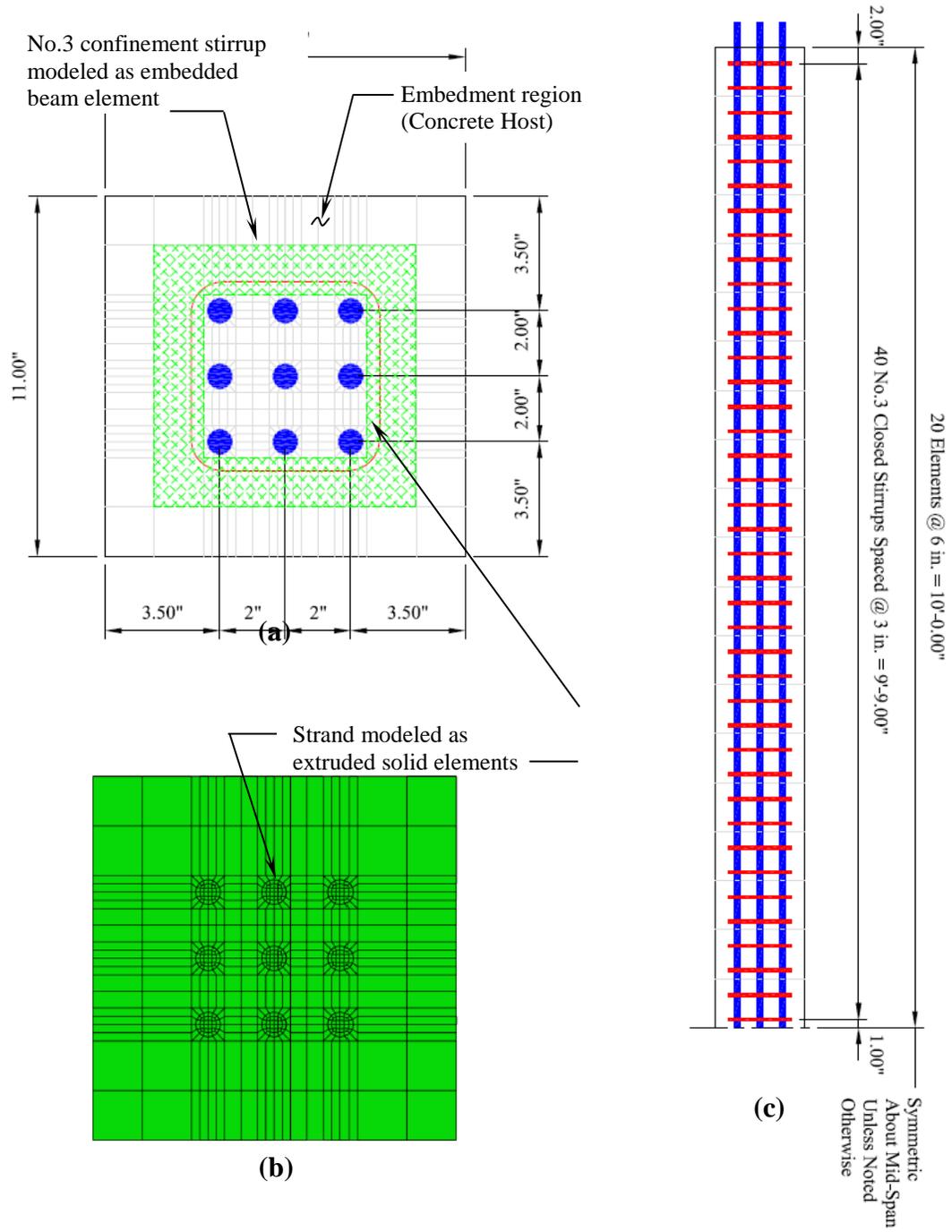


Fig. 10. Details of Class I [S200-U070-C3; S200-U140-C3] finite element models: (a) Typical cross section, (b) Finite element simulation, and (c) Layout of confinement reinforcement (No.3 closed stirrups spaced at 3 in. on center)

DISCUSSION OF RESULTS

The main objective of this section is to show a comparison of the response of the models immediately after release as the spacing of the released strands decreases from 2.80 in. to 2.00 in. The comparison is intended to provide insight for optimization of the strands spacing as the industry moves towards the use of larger diameter strands. Moreover, the effect of the confinement reinforcement (the amount and spacing) will be evaluated for each class of the finite element models.

Fig. 11 shows the comparison of the axial (compressive) strains of the concrete beams in response to nine 0.7-in. diameter strands spaced at 2.80 in. and 2.00 in. on center. The strains are measured along the mid-side of the finite element models. The analytical results correspond to the lower and upper boundary contact friction coefficients of 0.70 and 1.40, respectively. It is observed that the closer spacing of the strands (2.00 in versus 2.80 in.) does not significantly affect the axial (compressive) strains of the pretensioned concrete specimens with no confinement reinforcement. The numerical results also indicate that pretensioning stress convergences between 24 and 42 in. from the member ends based on the lower and upper boundary solutions, respectively. The obtained boundary values for transfer length are less than 60 times the strand diameter as recommended by AASHTO LRFD².

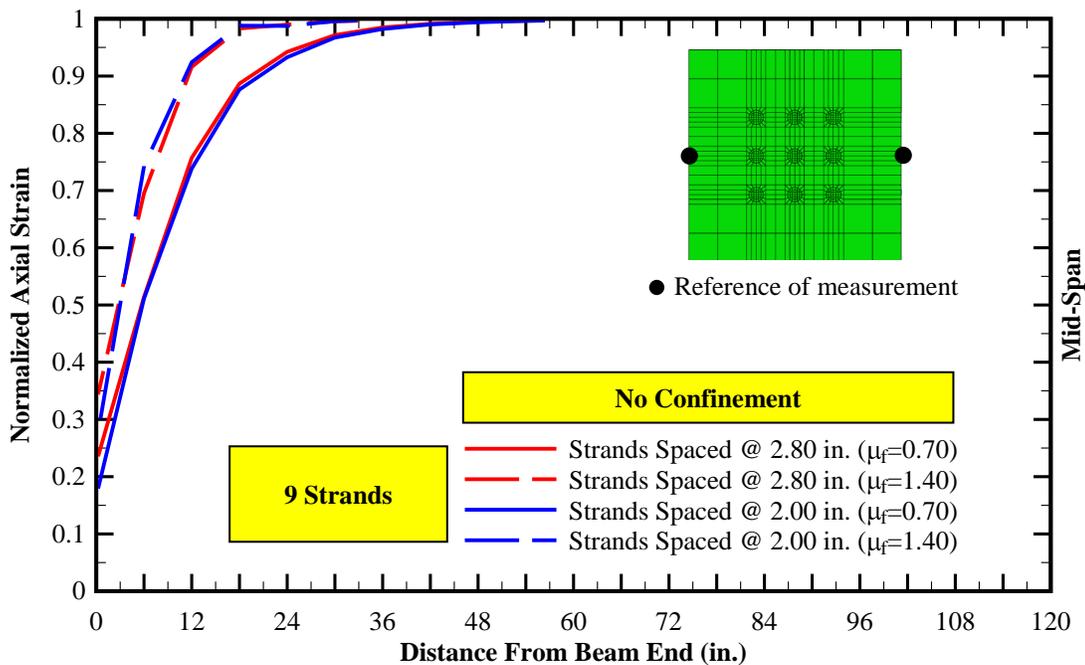


Fig. 11. Axial strains of Class I (strands spaced at 2.80 in.) and Class II (strands spaced at 2.00 in.) finite element models with no confinement reinforcement.

Fig. 12 and Fig. 13 show the comparison of the axial strains for Class I and Class II finite element models with various spacing of confinement reinforcement. Based on the analytical results, both classes of the finite element models indicate that the amount and spacing of the confinement reinforcement do not significantly affect the transfer length regardless of the strands spacing.

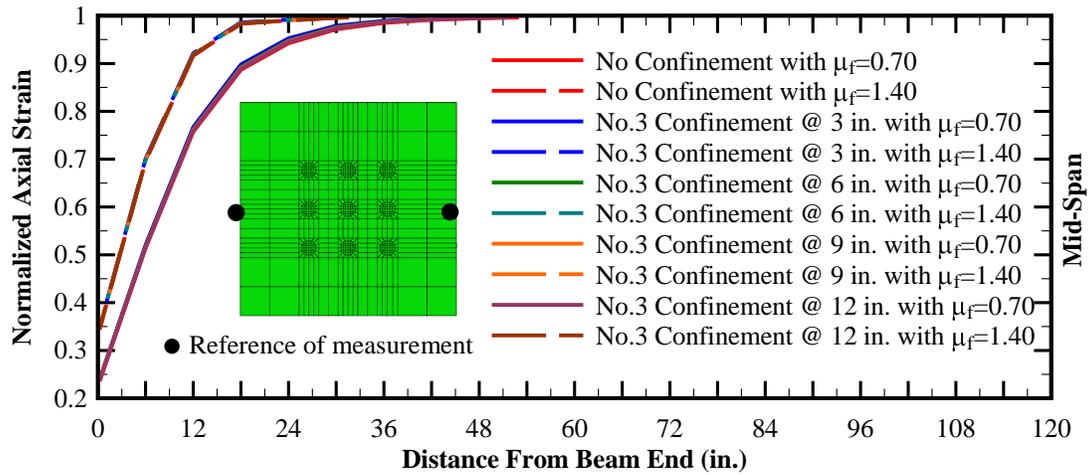


Fig. 12. Comparison of axial strains (transfer length) of Class I (nine 0.7-in. diameter strands spaced at 2.80 in. on center) with various spacing of confinement rebar.

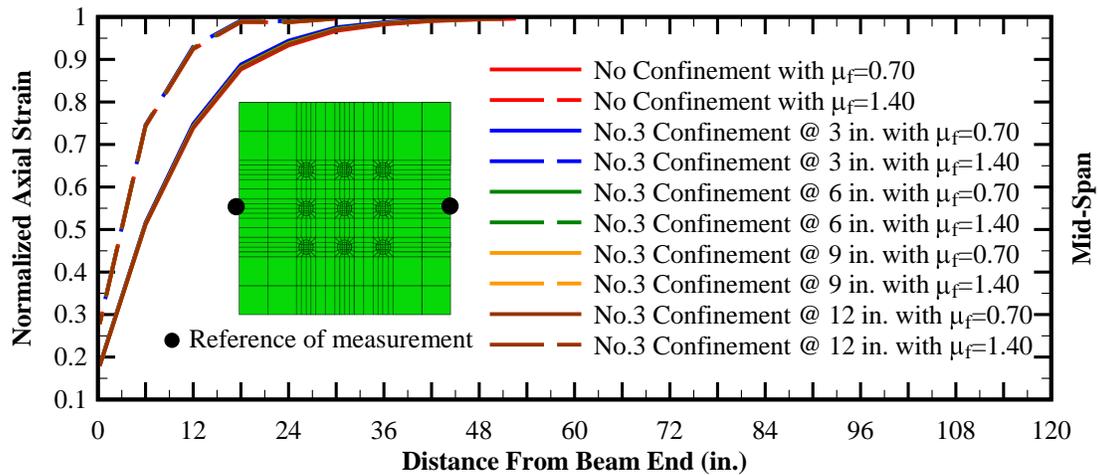


Fig. 13. Comparison of axial strains (transfer length) of Class II (nine 0.7-in. diameter strands spaced at 2.00 in. on center) with various spacing of confinement rebar.

When 0.7-in. diameter strands are spaced closer than four times the diameter, one of the major concerns is the tensile failure of the concrete between the strands due to lack of adequate clearance. In accordance with AASHTO LRFD², the maximum tensile stress in a fiber shall be limited to

$$F_t = 6\sqrt{f'_{ci}} = 537 \text{ psi} \tag{1}$$

Note that Equation (1) is applicable only if bonded tendons or reinforcement are readily available to withstand the imposed tensile stresses. In the case of the prestressed members, the confinement as well as vertical end zone and shear reinforcement are assumed to provide a basis for the applicability of the allowable tensile limits of Equation (1).

Fig. 14 shows the comparison of the lateral stresses observed in the vicinity of the mid-distance between the central strand and the exterior strand immediately above it while the specimen is unconfined. As it can be observed, the level of lateral tensile stresses may significantly increase (by as much as 240%) as the strands spacing decreases from 2.80 in. to 2.00 in. on center. This is further affected by the level of strand slippage. Nevertheless, it is observed that the upper boundary of tensile stresses approaches near but does not exceed the maximum allowable limit recommended by AASHTO LRFD².

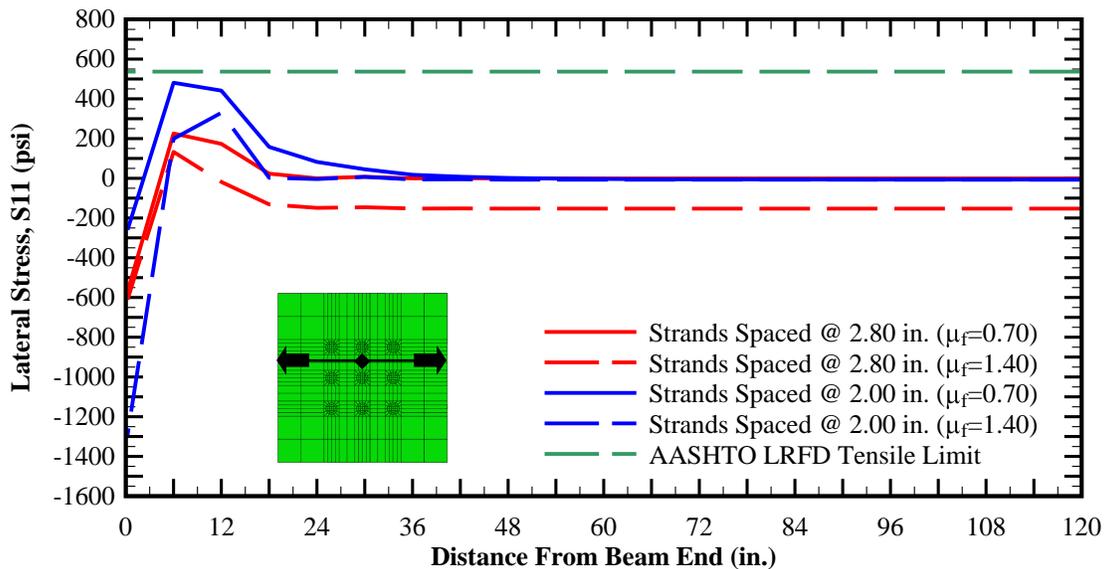


Fig. 14. Comparison of lateral stresses observed in Class I and Class II specimens with no confinement and immediately after the release of pretensioning.

Fig. 15 shows the trend of the lateral stress changes around the central strand corresponding to variations of confinement reinforcement. It can be observed that the upper and lower levels of tensile stresses are enveloped between the zero confinement and closely spaced (3.00 in. on center) confinement reinforcement as expected.

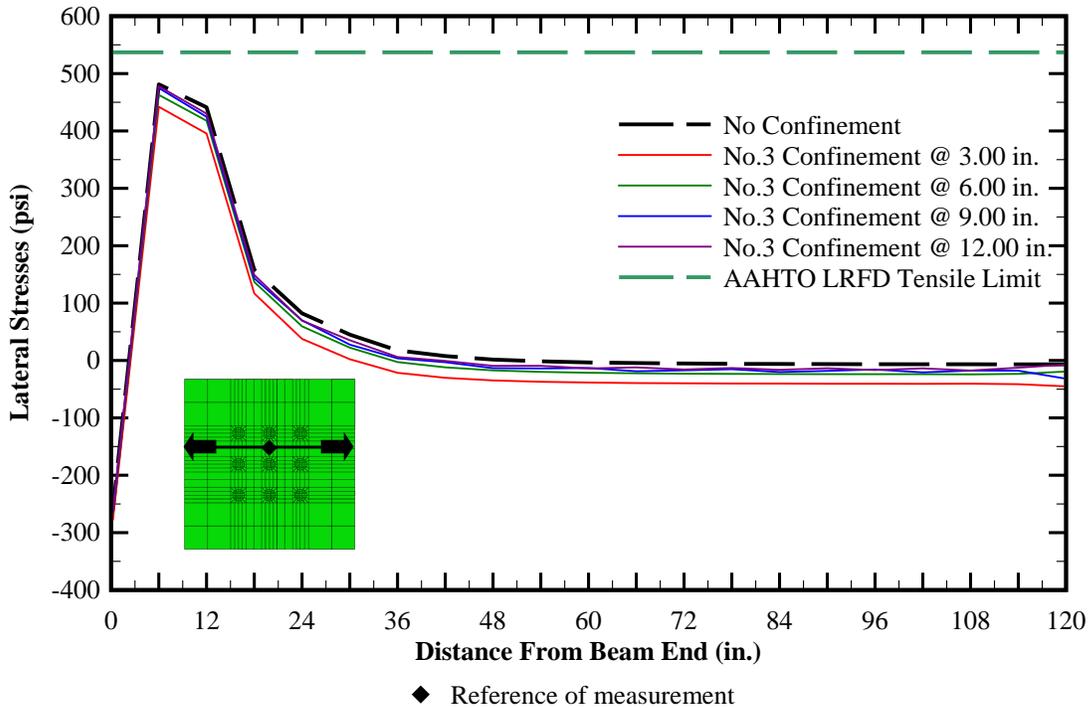


Fig. 15. The effect of confinement on the lateral stresses observed in Class II (strands spaced at 2.00 in.) with contact friction coefficient $\mu_f = 1.40$.

The analytical results show that the absence of confinement may further increase the magnitude of the imposed tensile stresses. As discussed above, in the absence of confinement reinforcement, the analytical results indicate that the unidirectional tensile stresses may increase by as much as 240% as the strands spacing is reduced from 2.80 in. to 2.00 in. on center. Meanwhile, similar simulations with confinement reinforcement comprised of No.3 closed stirrups show an increase of tensile stresses by as much as 165% regardless of the spacing of the confinement rebar.

Fig. 16 shows the comparison of maximum principal stresses obtained by Class I and Class II finite element models confined with No.3 closed stirrups spaced at 3 in. on center. Consistent with the previous results, the analytical results indicate that the state of tension may be significantly affected (increased) as the strands spacing is reduced from 2.80 in. to 2.00 in. Nevertheless, the anticipated changes of the tensile stresses are well below the allowable tensile limit recommended by AASHTO LRFD².

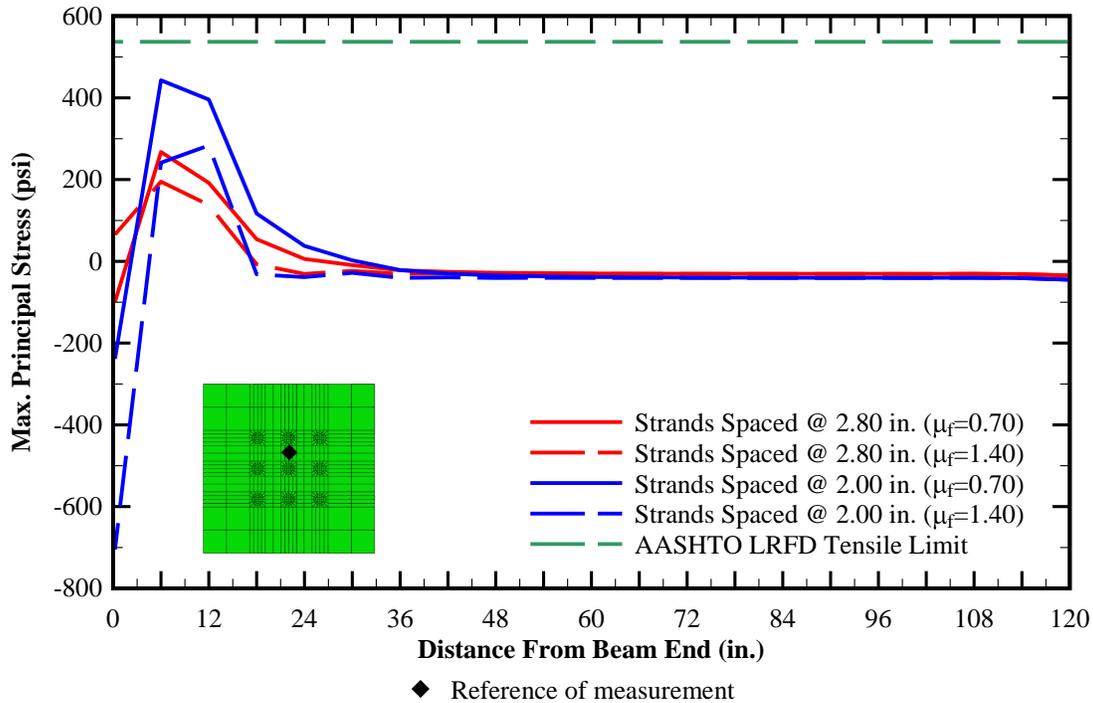


Fig. 16. Maximum principal stresses observed in Class I (strands spaced at 2.80 in.) and Class II (strands spaced at 2.00 in.) confined with No.3 stirrups spaced at 3 in.

Pressure is a deviatoric characteristic of material. It is defined as the average of lateral, vertical and axial stress components at any given point within the material matrix. The positive sign of deviatoric pressure indicates an overall state of the pressure. Under the state of positive pressure (compression) below the compressive strength of concrete (elastic regime), further compaction of cement paste within the concrete matrix is anticipated to be maintained.

Fig. 17 and Fig. 18 show the state of pressure around the central strand immediately after the release of pretensioning for Class I and Class II finite element models with upper boundary of strand slippage (minimum contact friction coefficient of $\mu_f = 0.70$), respectively. It is observed that the reduction of strands spacing from 2.800 in. to 2.00 in. on center significantly improves the state of pressure within the first 24 in. from the beam end.

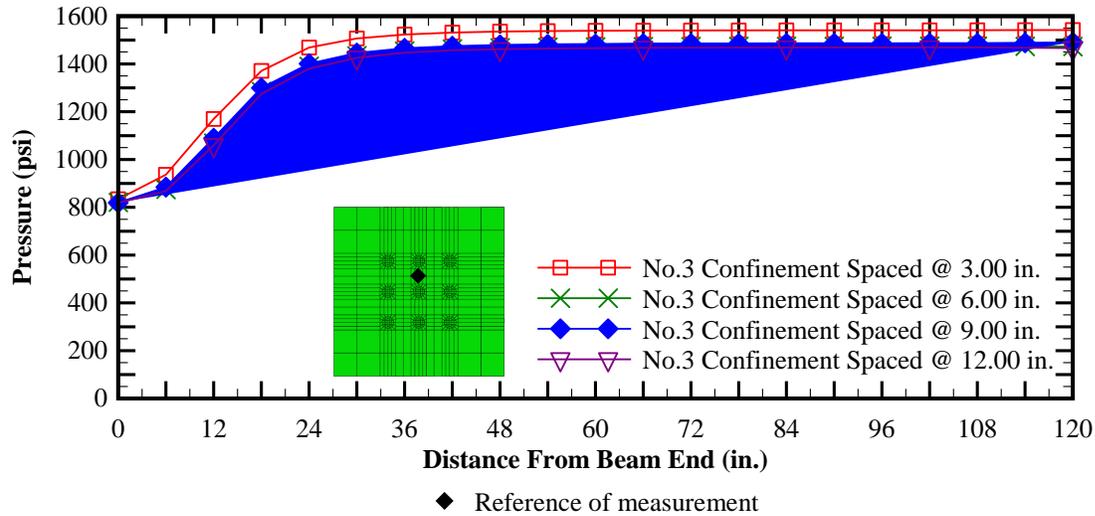


Fig. 17. Pressure observed in Class I (strands spaced at 2.80 in.) with various configuration of confinement reinforcement and upper slippage boundary ($\mu_f = 0.70$).

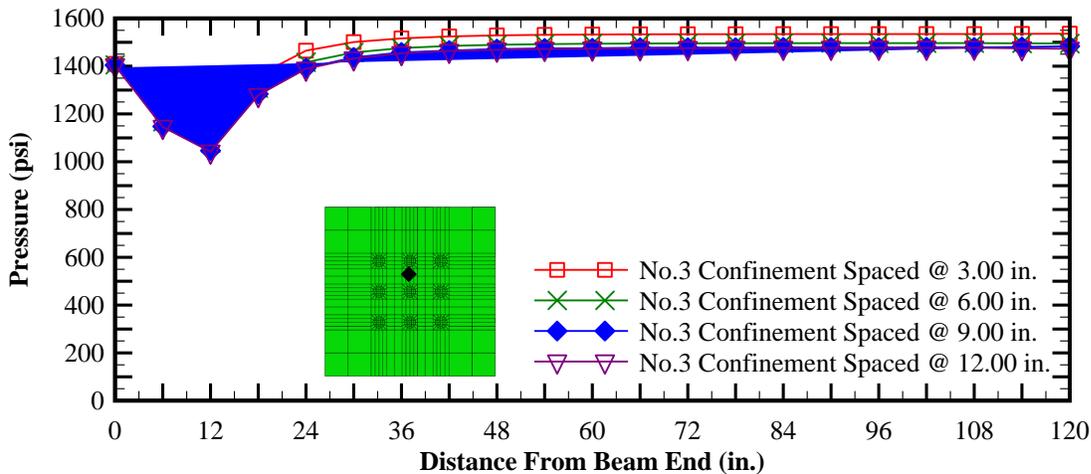


Fig. 18. Pressure observed in Class II (strands spaced at 2.00 in.) with various configuration of confinement reinforcement and upper slippage boundary ($\mu_f = 0.70$).

Additionally, Fig. 17 indicates a smooth increase of pressure distribution starting from the lowest values at end face of the member towards the maximum value near 42 in. from the member end face. Meanwhile, Fig. 18 indicates that as the strands are placed at closer spacing, the trend of pressure distribution changes.

It is important to note that the analytical results indicate that an overall state of compression (while varying in magnitude) is maintained around the central strands regardless of the spacing of the strands group. Meanwhile, the strands spacing is observed to result in notable alteration to the trend of pressure distribution along the end segments of the members. While pressure is not

generally used as a design parameter in common practice, it is an important measure affecting material dilation and volumetric changes. In general, areas experiencing moderate levels of pressure maintained below the compressive strength of concrete are less prone to tensile cracking due to sustained compaction of the cement around the aggregates.

CONCLUDING REMARKS

Based on the current guidelines for the design and detailing of prestressed concrete members, strands shall not be spaced closer than four times their diameter. This constitutes minimum strand spacing of 2.80 in. for 0.70-in. diameter strands. As a result, the precast producers will be required to apply significant and costly modifications to the current means and methods. In this research, the effect of reduced spacing of 2.00 in. for 0.70-in. diameter strands was studied, which conforms to the widely accepted reduced spacing for 0.60-in. diameter strands as well as the common setups in most of the precast yards across the U.S.

As the spacing of the strands decreases from 2.80 in. (four times the diameter) to 2.00 in., pronounced effects are observed in the stresses around the central strand. The analytical results show a notable increase (by as much as 165%) in the tensile stresses in the vicinity of the interior strand symmetrically surrounded by other strands. Meanwhile, depending on the strength of the concrete at the time of pretensioning release, the corresponding increase in the tensile stresses may be below the acceptable limits given by the current guidelines. Thus, the initial compressive strength of concrete at the time of pretensioning release is observed to be a critical parameter for using 0.7-in. diameter strands at 2.00 in. spacing which is less than the recommended four times the strand diameter. These analytical observations are consistent with the findings of the study conducted by Morcouc et al.³

The analytical results also indicate that the non-confined members show notable differences in the magnitude of the tensile stresses imposed by the pretensioned strands. Therefore, confinement reinforcement is found to be a critical component of the pretensioned members as required by the current state of practice.

In addition to the strands spacing, quality of the interface contact between concrete and strands is also observed to have notable effects on the level of the imposed stresses along the end segment of the specimens. As shown in this study, the surface friction values of 0.7 and 1.4 are anticipated to provide boundary interactions at the concrete-strand interface. Therefore, it is further recommended that the future models consider such boundary solutions or an average value if single iteration is desired.

Finally, the numerical simulations of a family of rectangular beam-columns, confined with No.3 closed stirrups spaced at 3.00 in. on center and pretensioned using 0.70-in. diameter strands, indicate that the transfer length of 0.70-in. diameter strands is anticipated to be between 24 and 42 in. from the member ends. Based on the finite element simulations, the spacing of the strands does not significantly affect the compressive strains of the specimens. However, the number of the strands and therefore, the magnitude of pretensioning affect the pretensioning path (transfer length mechanism) within the end zone of the member. The obtained boundary values for

transfer length are less than or equal to 60 times the strand diameter limit recommended. Additionally, the range of the analytical results hosts the transfer length of 31 in. for 0.70-in. diameter strands as recommended by **References 3-5**. Thus, it is concluded that 0.7-in. diameter strands may be potentially spaced at reduced spacing of 2-in. on center under certain conditions including minimum compressive strength of 10,000 psi. When the project economy allows for high strength concrete mixes, the use of 0.7-in. diameter strands may offer a notable measure for reducing the cost of pretensioning due to the efficiency and reduction of number of strands.

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