ASME B&PV CODE AND ACI STANDARD 359 TENDON INSTALLATION REVISION PROPOSAL

By

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For post-tensioning, ASME Boiler and Pressure Vessel Code Section III, Division 2, Subsection CC-4432.5, requires that horizontal circumferential tendon installation be conducted by twisting each strand or by pulling the bundled strands to minimize differential length of the individual strands. Revision to ASME Code CC-4432.5 tendon installation requirements is proposed to improve construction efficiency based on field experience, knowledge of initial jack application arrangement, and related post-tensioning standards and specifications.

INTRODUCTION

Large-scale civil structures such as long-span bridges, transfer girder, or slab in multi-story buildings, liquefied natural gas (LNG) tanks, and nuclear containment buildings use multistrand tendons in post-tensioning ducts. A multistrand tensioning jack, which uses gripping wedges inside the jack, simultaneously tensions each strand with the same stroke/force by moving out a steel plate. Theoretically, strands have the same elongation when a multistrand tensioning jack is used. However, actual tensile forces applied to individual strands within the tendon are not uniform. Tensile forces and effective elongation are influenced by tendon placement, installation, and means of tensioning.

Accordingly, post-tensioning-related organizations including Post-Tensioning Institute (PTI) and American Association of State Highway and Transportation Officials (AASHTO) provide their own requirements for post-tensioning tendon installation and tensioning methods (AASHTO 2017; PTI 2006; PTI/ASBI 2012).

With regard to nuclear containment buildings, design and construction, including the United States and South Korea, follow ASME Boiler and Pressure Vessel Code Section III, Division 2 (Joint ACI-ASME Committee 359 2019), which is also called the ACI Standard 359 (hereafter referred to as the ASME Code). The ASME Code covers overall design and construction. Subsections CC-2400 and CC-4400 provide requirements for the prestressing materials and construction of containment prestressing systems. Subsection CC-4432.5, the "Twisting and Coiling" requirement, addresses prestressing steel installation methods in the post-tensioning ducts. Depending on tendon locations, various layouts including horizontal circumferential tendon, vertical tendon, vertical inverted-U tendon, gamma tendon, and dome tendon are used (Fig. 1).

The most recent version of the ASME Code (2019 edition) states:

CC-4432.5 Twisting and Coiling

(a) *Prestressing tendons composed of multiple elements shall be twisted, as necessary, to minimize differential length of the individual prestressing steel elements. Twisting is mandatory for all horizontal circumferential tendons composed of multiple elements stressed simultaneously as a group. The amount of twist shall be specified in the construction procedure. However, intentional twisting of tendons composed of multiple elements stressed simultaneously as a group may be waived for horizontal circumferential tendons as well as other configurations of tendons meeting all other requirements of CC-4430 provided the following additional conditions are met:*
   (1) *Tendons shall be maximum 0.63 in. (16 mm) strand (ASTM A416) that are prefabricated and pulled into the duct at one time (complete tendon). All strands shall be the same hand lay.*
   (2) *Provisions shall be made to keep strands in the tendon bundle parallel as the tendon is pulled into the duct.*
   (3) *The uncoiler shall allow individual strands to move against each other as the tendon is pulled in. The tendon shall be pulled from a cage versus being pre tied and pulled in from a rotating table (lazy susan).*

(b) *Coiling, when required for transportation, shall be performed in a manner not to cause damage to the tendon. Coil diameter shall be specified in the construction procedures.*

To minimize differential lengths of the individual strands (to minimize tensile force variation in the

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individual strands of a tendon), the ASME Code requires all horizontal circumferential tendons to be installed by twisting all comprising prestressing strands as shown in Fig. 2. The twisting requirement may be waived only if maximum 16 mm (0.63 in.) diameter strands (ASTM A416) are prefabricated (bundled) and pulled into the duct at once.

Due to working space needs to accommodate placement of equipment such as a pulling winch, it is difficult to meet said criteria in the field during construction, particularly for horizontal tendons inserted into ducts high above the ground. Also, a more reasonable installation and tensioning method (that is, use of initial arrangement jack) is available that can minimize differential tensile forces in individual strands.

The ASME Code requirement is very rigid in many aspects when compared to other standards and specifications (AASHTO 2017; AFCEN 2012; EOTA 2006a,b; PTI 2006; PTI/ASBI 2012). Researches on elongation and differential tensile forces in individual strands has also been reported (Cho et al. 2015; Cho et al. 2016; Domage et al. 2010; Domage et al. 2013; Hayek and Kang 2017). Thus, in this study, revision to the ASME Code CC-4432.5 tendon installation requirement is proposed.

CURRENT CODE PROVISIONS AND ISSUES

Purpose of tendon installation requirement in ASME Code Subsection CC-4432.5

In horizontal curvilinear multistrand tendons having multiple strands, differential elongations and deviation of tensile forces in the individual strands are inevitable. The first reason is the difference in length between strands inside and outside the duct (Fig. 3(a)). If the difference between the radii of innermost and outermost strands is ΔR, the maximum difference in length in a 360-degree horizontal circumferential tendon is $2\pi\Delta R$ (Domage et al. 2010). For induced tendon elongation ΔL, tensile stresses applied to the innermost and outermost strands may be calculated using Eq. (1) and (2), from which the maximum difference of individual strand stresses may be obtained from Eq. (3).

$$\sigma_{(1)} = \frac{(2\pi R - \pi\Delta R) + \Delta L}{2\pi R - \pi\Delta R} E_p \tag{1}$$

$$\sigma_{(2)} = \frac{(2\pi R + \pi\Delta R) + \Delta L}{2\pi R + \pi\Delta R} E_p \tag{2}$$

$$\Delta\sigma = \sigma_{(1)} - \sigma_{(2)} = \frac{2\pi\Delta R\Delta L E_p}{(2\pi R)^2 - (\pi\Delta R)^2} \tag{3}$$

where $\sigma_{(1)}$ and $\sigma_{(2)}$ are the applied stresses of innermost and outermost strands in a tendon, respectively; $\Delta\sigma$ is the maximum difference of individual strand stresses; R is the radius of tendon; and E_p is the modulus of elasticity of prestressing strands.

Individual strand force deviations may also be attributed to strands located on the outside of a curved tendon moving inward under tensioning (Fig. 3(b)) and strands irregularly arranged being stretched straight in a duct during tensioning (Fig. 3(c)).

Given a multistrand tensioning jack applies the same elongation with a hydraulic piston and the same stroke, simple movements at the end of strands occur due to the removing of initial slack. These "fake elongations" correspond to the gray portions of Fig. 3(b) and (c). The gray portion of elongation depicted at the end of the strand in the figures does not contribute to the tensile force applied to the strand. However, this discussion does not

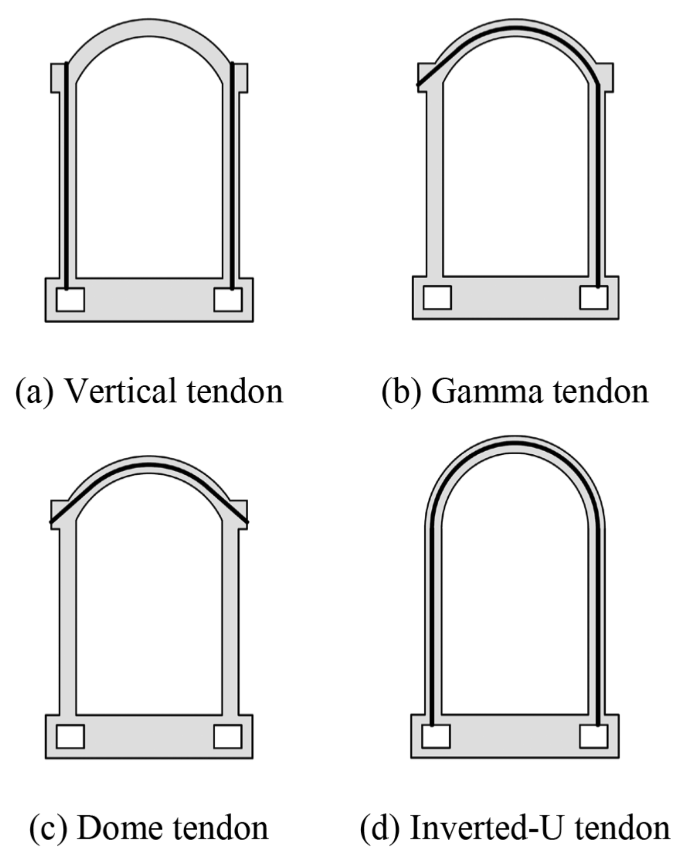
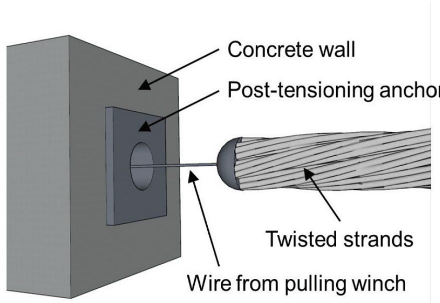
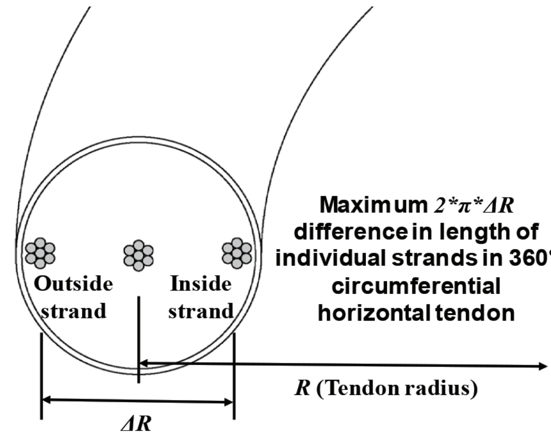


Fig. 1–Various layouts of vertically installed tendons.

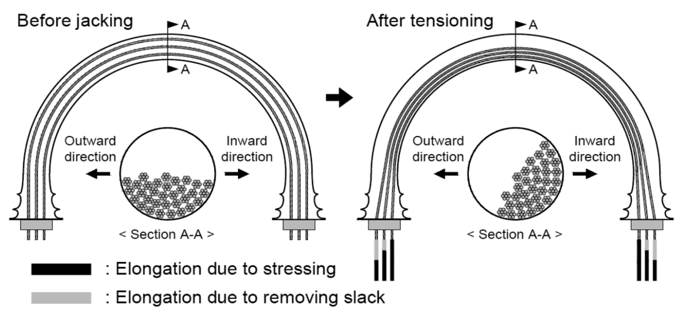


(a) Tendon installation of twisted strands

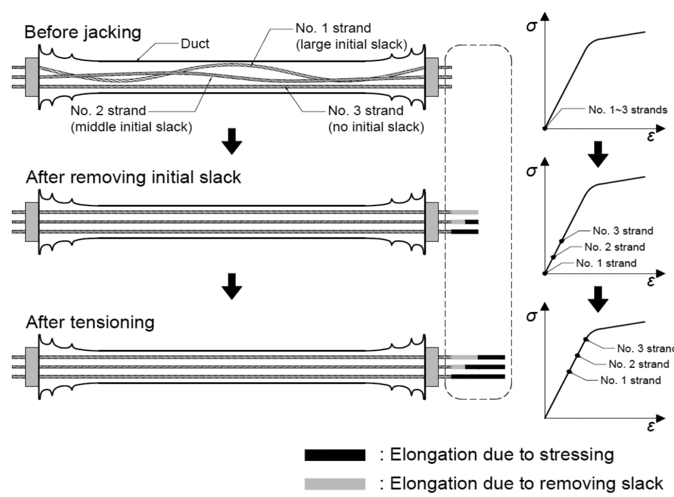
(b) Twisted seven-wire strands (http://www.fwmetals.com)
Fig. 2—Tendon installation by twisting all comprising strands.



(a) Differential length between inner and outer strands (Domage 2016)



(b) Initial slack due to curvature



(c) Initial slack due to non-straight placement of strands

Fig. 3—Causes of differential lengths and tensile stresses in individual strands of tendon.

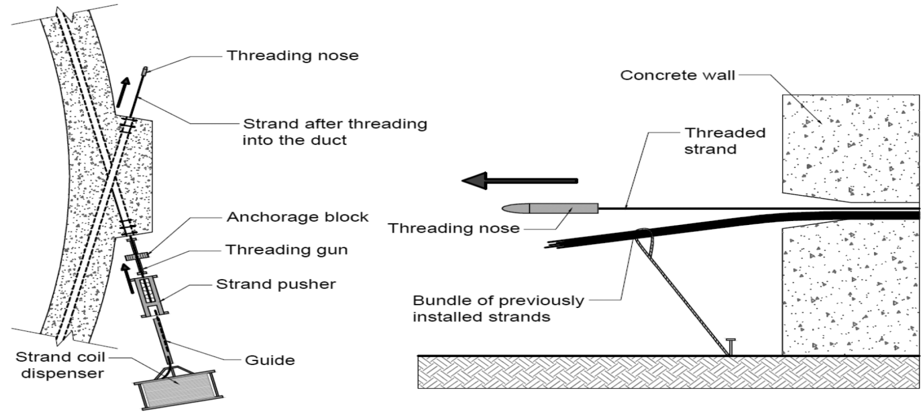
apply to vertical tendons that may have minor deviations but are essentially straight. Because the radius (R) of tendon is very large and the cumulative angular change (α) of tendon is negligible, deviations related to Eq. (3) are very small. Additionally, due to the straight initial placement of individual strands, vertical tendons tend to have limited initial slack.

ASME Code Subsection CC-4432.5 requires twisting all horizontal circumferential tendons because twisting of all strands in a tendon will minimize the difference in length between the individual strands. Because the individual strands cannot move respectively to each other, there is almost no deviation even during the inward movement of the twisted strands in a circumferential duct.

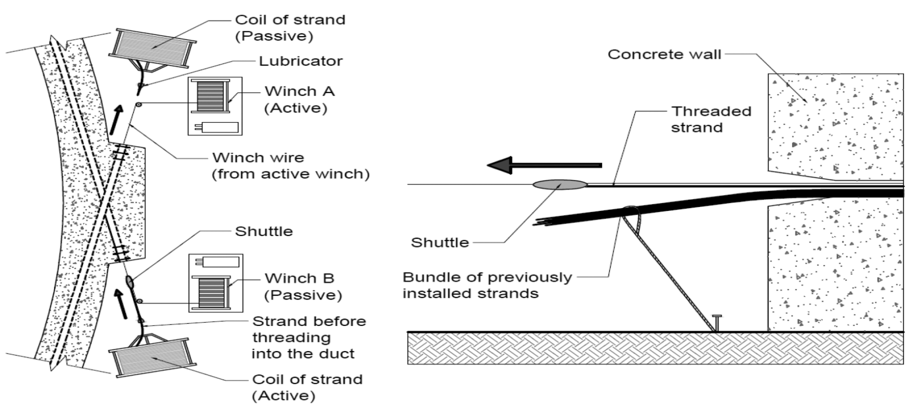
Issues with ASME Code Subsection CC-4432.5

A horizontal circumferential tendon of nuclear containment building consists of dozens of strands, with lengths typically exceeding 100 m (328 ft). For example, a containment building of APR 1400 reactor type (South Korea) has 105 m (345 ft) long horizontal circumferential tendons with forty-two 15.2 mm (0.60 in.) diameter seven-wire strands; VVER 1000 reactor type (Russia) has 149 m (489 ft) long tendons with fifty-five 15.7 mm (0.62 in.) diameter seven-wire strands; and the EPR reactor type has 158 m (518 ft) long tendons with fifty-five 15.7 mm (0.62 in.) diameter seven-wire strands.

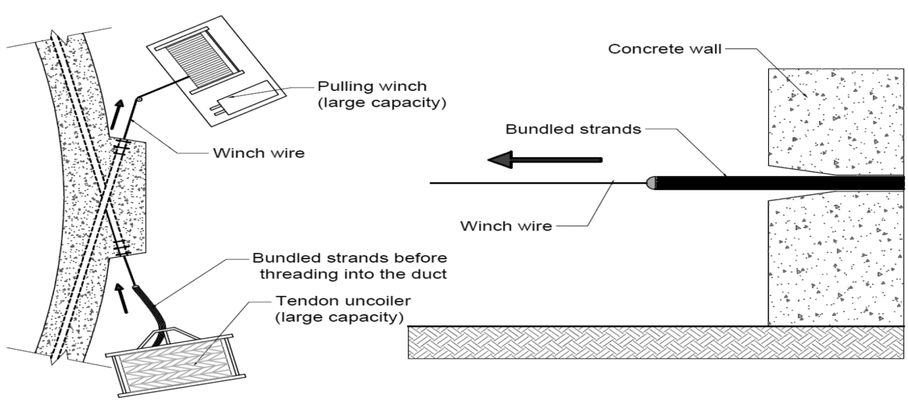
Due to the tendon length and associated weight, significant working space for equipment such as a tendon uncoiler, tugger, and pulling winch is required to twist the strands. Particularly, horizontal circumferential tendons are set using a working platform carrying the aforementioned equipment that climbs the buttress of



(a) Pushing individual strands



(b) Pulling individual strands



(c)Pulling bundled strands

Fig. 4—Tendon installation methods used in post-tensioning construction fields.

the concrete wall. Working space required is one of the major factors that make tendon installation procedure difficult, leading to inefficiency in construction.

Alternative methods are desired in construction. In practice, pushing/pulling individual strands or pulling bundled strands without twisting (Fig. 4) is performed by post-tensioning construction companies. Usually, pushing individual strands is preferred for horizontal tendons, as it requires small-capacity equipment but allows very fast installation (no round trip). The strands pushed by a threading gun (refer to Figure 4(a)) may be stuck by the preinstalled strands in the duct, or hit the duct hard. The method of pushing individual strands is not applicable to vertical tendons because it requires heavy equipment that must withstand strand's gravity when pushing upward.

In practice, initial slack and tensile force deviation are removed by use of an initial arrangement jack (Fig. 5). Because tendons are composed of more than 37 strands (typically 42 or more up to 55 strands per tendon), the use of it can also reduce the number of strokes after multistrand stressing using a jack with at least a 500 mm (20 in.) stroke. Said methods are currently not allowed by the current ASME Code CC-4432. However, recognition and integration of said practice is desirable to increase construction efficiency and convenience, particularly in South Korea, where the ASME Code is actively adopted for nuclear containment construction. Table 1 summarizes prior field experiences of the tendon installation methods applied for nuclear power plants. Note that when "pushing strand by strand" is indicated, pulling method is also feasible and the better choice made is linked to the possibilities that offer to position the strand coil for threading.

BACKGROUND ON REVISION PROPOSAL

Field experience on construction of post-tensioned nuclear containments

In past nuclear containment construction around the globe, pushing individual strands (strand by strand) or pulling bundled strands installation methods have been used. For horizontal circumferential tendons, the method of pushing strand by strand has been mainly used in EPR,

Table 1—Field practice on tendon installation in nuclear containment building construction (courtesy of Ivica Zivanovic, Freyssinet International, for first four nuclear reactor types)

Nuclear reactor type	No. of strands in a tendon (each)	Diameter of strands, mm	Filling material in post-tensioning duct	Tendon installation method
EPR	55	15.7	Cement grout	(H)(V)(G) Pushing strand by strand
VVER 1000	55	15.7	Cement grout	(H) Pushing strand by strand (V) Pulling bundled strands
VVER 1200	55	15.7	Cement grout (individual strands are greased and PE-coated)	(H) Pulling strand by strand and pulling bundled strands (V) Pulling bundled strands
CPR 1000	37	15.7	Cement grout	(H)(V)(D) Pushing strand by strand
OPR 1000 (KEPCO-DOOSAN)	55	12.7	Flexible filler (grease)	(H)(V) Pulling bundled strands
APR 1400 (KEPCO-DOOSAN)	42	15.2	Flexible filler (grease)	(H)(V) Pulling bundled strands

Note: 1 mm = 0.0394 in.; (H) is horizontal circumferential tendon; (V) is vertical or inverted-U tendon; (G) is gamma tendon; (D) is dome tendon.

VVER, and CPR 1000 nuclear reactor types for European countries which adopt ETC-C (AFCEN 2012), while the method of pulling bundled strands has been mainly used in US APWR, OPR 1000, and APR 1400 nuclear reactor types for the United States and South Korea, which adopt the ASME Code.

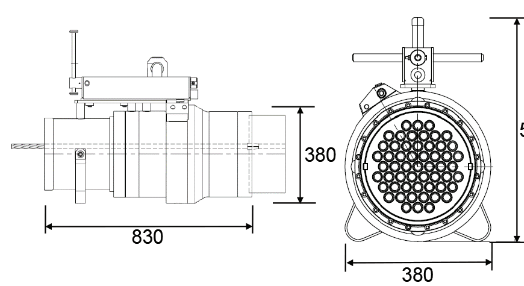
For vertical tendons including inverted-U tendon, gamma tendon, and dome tendons, the method of pulling bundled strands has been primarily used regardless of countries and applying codes.

In the case of LNG tank concrete structures, horizontal circumferential tendons are installed by pushing individual strands, while vertical tendons are installed by pulling bundled strands. Figure 5 shows Freyssinet Korea's field experiences on tendon installation in LNG tank post-tensioning construction.

It is convenient and preferred by post-tensioning contractors to push or pull individual strands for horizontal tendons and pull bundled strands for vertical tendons for large-scale civil structures due to difficulty in twisting strands in the field in accordance with current ASME Code CC-4432.5. As such, modification of ASME code requirements to address current post-tensioning construction techniques is desired.

To address individual strand force deviation, post-tensioning constructors often use the initial arrangement jack to remove initial slack before the main tensioning operation. The initial arrangement jack (Fig. 5) tensions each strand with the same pressure using individual hydraulic piston. Individual tensioning with a low force equal to approximately 5 to 10% of the tensile strength (f_{pu}) of prestressing strands creates approximately the same level of initial tensile stress in all strands.

(a) Application of initial arrangement jack (courtesy of Freyssinet Korea)



(b) Freyssinet International's initial arrangement jack (drawings of 55C15 Equitension jack) (EOTA 2006b)

Fig. 5—Initial arrangement jack.

Table 2 identifies where the initial arrangement jack has been used in nuclear containment post-tensioning construction. For the Shinhanul Units 1 and 2 (South Korea) and Barakah Units 1, 2, 3, and 4 (UAE), tendon installation was conducted by pulling bundled strands,

Table 2—Field experiences on initial arrangement jack application in nuclear containment building construction (Domage 2016)

Project	Applied standards	Tendon arrangement	Tendon length, m	Strand diameter, mm	No. of strands	PT supplier
Olikuoto 3	ETC-C	Horizontal circumferential, 360 degrees	158	15.7	54	Freyssinet International
Flamanville 3	ETC-C	Horizontal circumferential, 360 degrees	158	15.7	54	Freyssinet International
Taishan 1-2	ETC-C	Horizontal circumferential, 360 degrees	158	15.7	54	Freyssinet International
Tianwan 1-2	ASME	Horizontal circumferential, 360 degrees	149	15.7	55	Freyssinet International
Tianwan 3-4	ASME	Horizontal circumferential, 360 degrees	149	15.7	55	VSL International
Shinhanul 1-2	ASME	Horizontal circumferential, 270 degrees	105	15.2	42	VSL International
Barakah 1-4	ASME	Horizontal circumferential, 270 degrees	105	15.2	42	VSL International

Note: 1 m = 39.4 in.; 1 mm = 0.0394 in.

(a) Pushing individual strands for horizontal circumferential tendon *(b) Pulling bundled strands for vertical tendon*

Fig. 6—Freyssinet Korea's field experience on tendon installation in LNG tank construction (courtesy of Freyssinet Korea).

whereas the others were installed by pushing individual bare strands.

Experimental verification on use of initial arrangement jack

Domage et al. (2010) performed a full-scale mockup experiment that included measurement of individual strand forces in horizontal circumferential tendons as part of nuclear containment building. The test specimen was a ring-shaped containment wall shown in Fig. 7. Tendons consisted of 55 to 15.7 mm (0.5 in.) diameter seven-wire bare strands, 158 m (518 ft) long, and angular change of 369.6 degrees. An initial arrangement jack was applied to remove slack in some of the tendons and forces applied to the individual strands were measured with 55 individual electromagnetic sensors (EM sensors) attached to the multistrand tensioning jack.

Figures 7(a) and (b) show the distribution of strand forces measured at 45% of the tensile strength of prestressing strands (f_{pu}). Figures 7(a) and (b) show distribution of tension forces for the cases when the initial arrangement jack was not used and used, respectively. For the latter case, a significant coefficient of variation (COV) of 27.5% was measured, whereas the former showed a low COV of 6.7%. The application of the initial arrangement jack successfully reduced the differential tensile stresses in the strands.

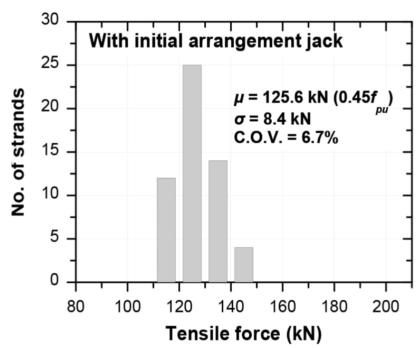
Data of initial slack and its removal in actual nuclear containment building

A previous case of initial arrangement jack application in Shinhanul nuclear power plant Units 1 and 2 in South Korea is reported in this study. To correct differential initial length, an initial arrangement jack was applied before main tensioning of the tendons, strands. The initial arrangement jack used in the construction was VSL International's product, called "low force jack", which is capable of tensioning up to 55 strands with 13.52 kN (3 kip) per strand using up to 65 MPa (9.4 ksi) capacity pistons. Each piston has an individual piston area of 208 mm^2 (0.32 in^2) and a stroke range up to 120 mm (4.7 in.).

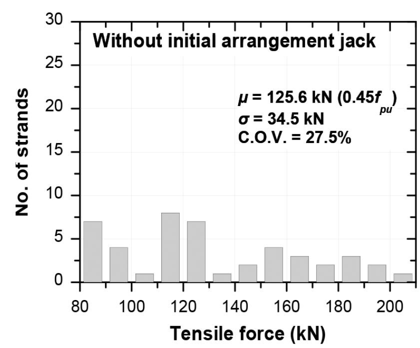
For the Shinhanul nuclear power plant, differential lengths were measured for 390 horizontal circumferential tendons and 200 vertical inverted-U tendons. Each tendon was composed of 42 to 15.2 mm (0.60 in.) diameter strands. Figure 9 shows initial slack measurement process for the horizontal circumferential tendons (Fig. 9(a)) and vertical inverted-U tendons (Fig. 9(b)). By measuring movement of the paint markers at the end of the individual strands before and after using the initial arrangement jack, initial differential lengths of the individual strands were measured. The greater the distance in positions of the paint markers, the larger initial differential length. Movement of the marker due to operation of the initial arrangement jack indicates length of removed initial slack. Data from Shinhanul nuclear power plant is depicted in Table 3. The difference between maximum and minimum distances of individual strands in a tendon is defined as d. Larger d values were indicative of increased initial slack and irregularity in installation.

As shown in Fig. 9 and Table 3, there was little difference between the maximum and minimum moving distance,

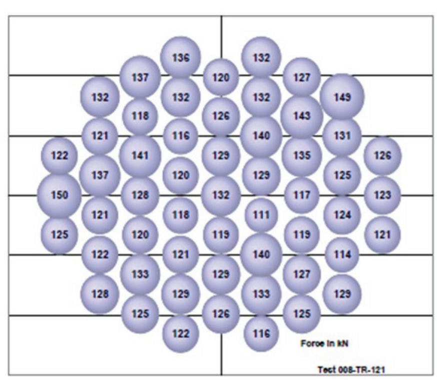
Fig. 7—Full-scale mockup specimen of nuclear containment building (Domage et al. 2010).



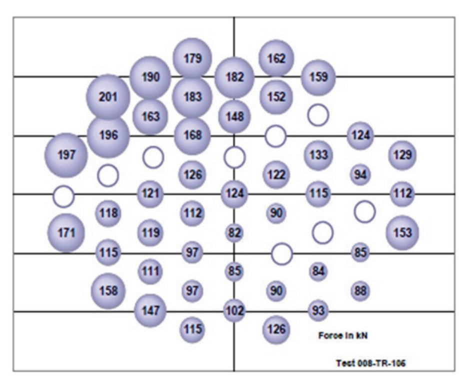
(a) Distribution of individual strand tensile forces with use of initial arrangement jack



(b) Distribution of individual strand tensile forces without use of initial arrangement jack

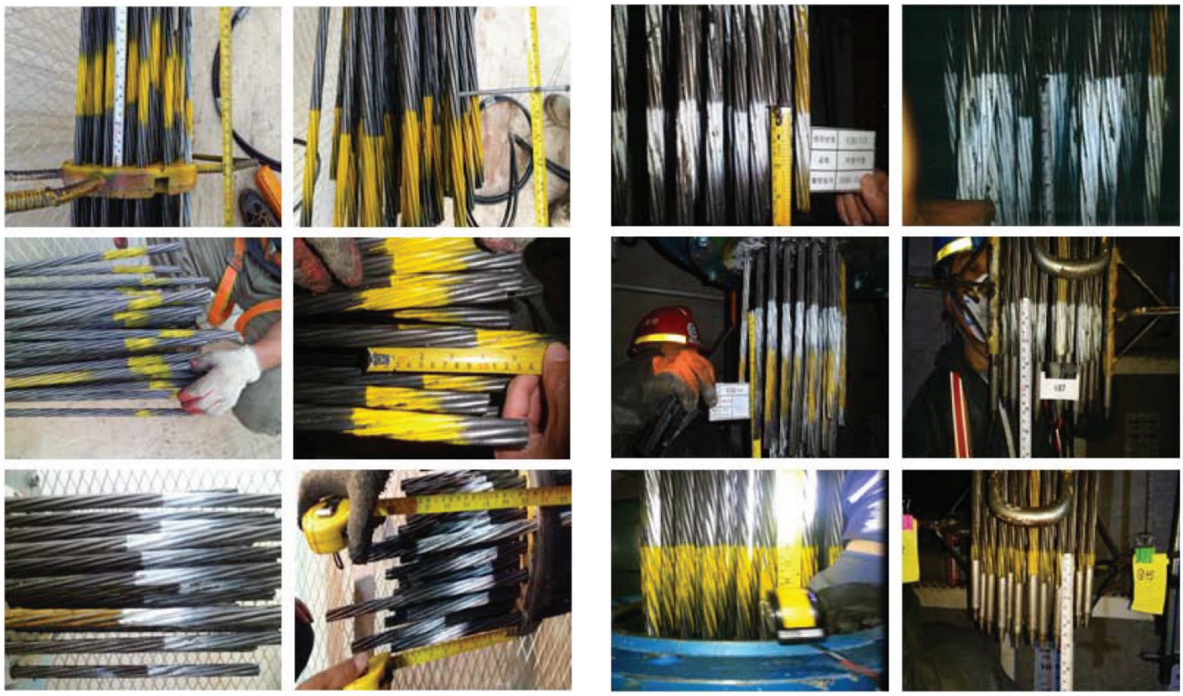


(c) Measured individual strand tensile forces with use of initial arrangement jack



(d) Measured individual strand tensile forces without use of initial arrangement jack

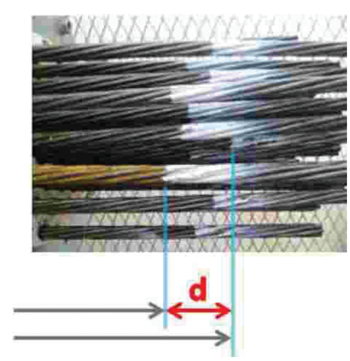
Fig. 8—Effect of initial arrangement jack on distribution of individual strand tensile forces (Domage et al. 2010).



(a) Horizontal circumferential tendons *(b) Vertical inverted-U tendons*

Fig. 9—Field measurement after application of initial arrangement jack in actual nuclear containment building construction (Shinhanul nuclear power plant Units 1 and 2).

Table 3—Initial slack measurement in Shinhanul nuclear power plant Units 1 and 2

Maximum differential length, mm	Horizontal circumferential tendon (each)	Vertical inverted-U tendon (each)	Remark
$d = 0$	0	67	
$0 < d \leq 12.7$	0	125	
$12.7 < d \leq 25.4$	8	6	
$25.4 < d \leq 38.1$	19	1	
$38.1 < d \leq 50.8$	49	0	
$50.8 < d \leq 76.2$	114	1	
$76.2 < d \leq 101.6$	113	0	
$101.6 < d \leq 127.0$	65	0	
$127.0 < d \leq 152.4$	15	0	
$152.4 < d \leq 177.8$	5	0	
$177.8 < d$	2	0	
Total	390	200	

Note: 1 mm = 0.0394 in.; average jacking force of tendon is $0.8f_{pu}A_{ps}$ = 8760 kN/tendon (= 208.6 kN/strand), where f_{pu} is tensile strength of tendon and A_{ps} is cross-sectional area of tendon; vertical tendon: d = 10 mm → difference in tensile force of approximately 1.8 kN per strand (approximately 0.9 % of average tensile force); measured strand elongation ranged from 990 to 1170 mm at $0.8f_{pu}$ jacking force; horizontal tendon: d = 10 mm → difference in tensile force of approximately 3.4 kN per strand (approximately 1.6 % of average tensile force); measured strand elongation ranged from 460 to 610 mm at $0.8f_{pu}$ jacking force.

Vertical inverted-U tendon: d = 10 mm → difference in tensile force of approximately 1.8 kN per strand (approximately 0.9 % of average tensile force); The measured strand elongation ranged from 990 to 1170 mm at $0.8f_{pu}$ jacking force.
Horizontal tendon: d = 10 mm → difference in tensile force of approximately 3.4 kN per strand (approximately 1.6 % of average tensile force); The measured strand elongation ranged from 460 to 610 mm at $0.8f_{pu}$ jacking force.

d, for vertical inverted-U tendons before and after the initial arrangement jack application. The individual vertical tendon strands of dome tendon, gamma tendon, and vertical inverted-U tendon are driven inward due to gravity after installation (refer to Fig. 10), making distribution uniform without local curvature or slack in the individual strands. Given the direction in which the strands are pulled is also in the direction of gravity, no significant changes in the arrangement of the strands were noted. Although the straight vertical tendon strands are not driven inward due to gravity or tensioning, the strands are essentially straight after installation and initial slack is negligible. As is, individual force deviation due to initial slack was very limited in the vertical inverted-U tendons. Thus, there is no need to apply any specific installation method or use an initial arrangement jack to reduce the differential tensile forces in vertically installed individual vertical strands.

Whereas, in horizontal circumferential tendons, as shown in Fig. 4(b), significant change in the

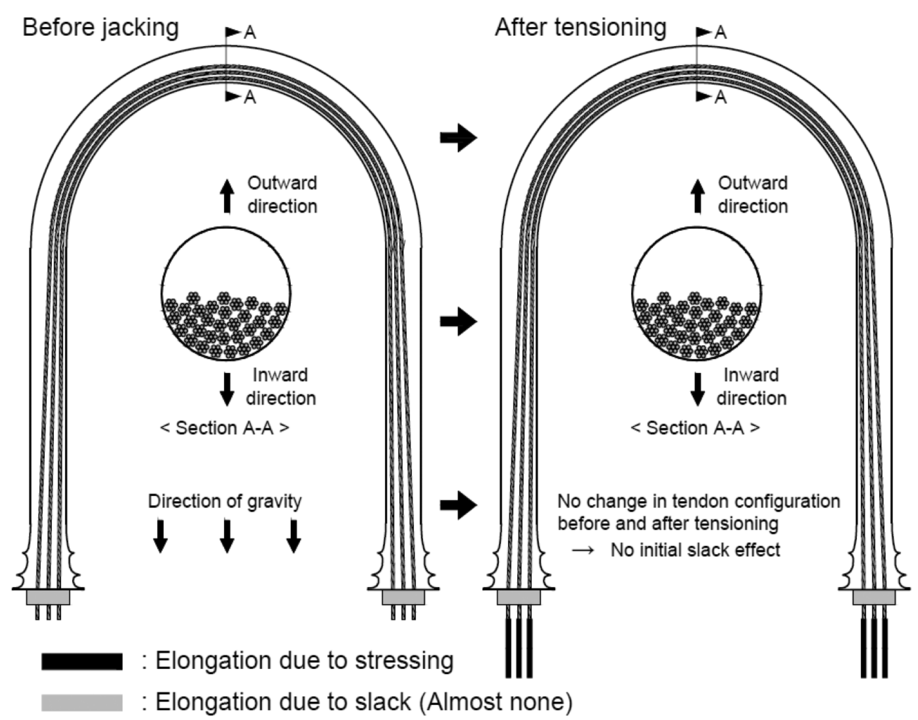


Fig. 10—Arrangement of individual strands in vertical inverted-U tendon before and after tensioning.

Table 4—Tendon installation and preliminary tensioning requirements in standards and specifications (summary)

Standards/Specification		Tendon installation (threading) method: Twisting	Pulling bundled strands	Pushing individual strands	Pulling individual strands	Preliminary tensioning (use of initial arrangement jack)
ASME (2017)	Horizontal circumferential tendon	Specified	Specified	Not permitted	Not permitted	—
	Vertical tendon	—	—	—	—	—
ETC-C (AFCEN 2012)		—	—	Specified	—	Required
Post-Tensioning Manual (PTI 2006)		—	Specified	Specified	Specified	—
PTI/ASBI M50.3 (PTI/ASBI 2012)		—	Specified	Specified	Specified	—
AASHTO LRFD Bridge Construction Specifications (AASHTO 2017)		—	—	Specified	Specified	Required
FHWA Post-Tensioning Tendon Installation and Grouting Manual (FHWA 2013)		—	Specified	Specified	—	—
ETA 06-0006 (EOTA 2006) (VSL International's construction specification)		—	Specified	Specified	—	—
ETA 06-0226 (EOTA 2006) (Freyssinet International's construction specification)		—	Allowed*	Allowed*	Allowed*	Specified

*Not mentioned in ETA 06-0226 but in working procedure, as ETA 06-226 does not cover installation method.

Note: 1 m = 39.4 in.; 1 mm = 0.0394 in.; "—" is not mentioned.

arrangement of individual strands before and after tensioning was anticipated. However, the need to adhere to the requirements of ASME Code CC-4432.5 was not necessitated due to effective reduction in individual strand force deviation based on field experience and experimental verification (Domage et al. 2010) through use of an initial arrangement jack.

Other standards and specifications related to tendon installation

Summarization of requirements for post-tensioning-related standards and specifications pertaining to tendon installation methods are provided in Table 4. Only the ASME Code requires all horizontal circumferential tendons to be twisted. The majority permit installation methods by pushing or pulling individual strands or pulling bundled strands without twisting.

In particular, ETC-C (AFCEN 2012), the construction code for concrete nuclear containment buildings in Europe, does not require twisting strands or bundling strands after installation. According to ETC-C, Section 2.5.3.4.1 (AFCEN 2012) (refer to Table 5), tendons can be installed by pushing individual strands in a duct or the installation procedure can be controlled by the post-tensioning supplier, and preliminary tensioning is required using a special device that can simultaneously tension strands with individual displacement before main tensioning. In short, use of initial arrangement jack may be applied.

Table 5—Preliminary tensioning requirements in standards and specifications

Standard/Specification	Requirement
ETC-C (AFCEN 2012)	**2.5.3.4 Tensioning** **2.5.3.4.1 Execution** Tensioning shall be performed with the aid of a hydraulic jack, fully compatible with the anchorage block of the system, in accordance with the programme defined by the designer, who specifies the order of tensioning and the calculated elongation. The prestressing system, including jacks, shall be tested in order to prove it is suitable for works and to limit the differential loading between strands. The following aspects shall be tested: - Its implementation in all situations encountered during works, - Initial simultaneous tensioning of each strand of a tendon, with individual displacements of each strand inducing a load between 10 and 15 kN for each strand at the anchorage, - Tensioning of the strands in a single stroke of the jacks (at least 500 mm) without recovery of tensioning, - The suitability for works of the jacks to satisfy the specifications shall be justified. This justification shall be based on tests and include friction loss measurements in the jacks.
AASHTO LRFD Bridge Construction Specifications (AASHTO 2017)	**10.10.1.4-Measurement of Stress** (The former part is omitted) All tendons shall be tensioned to a preliminary force as necessary to eliminate any take-up in the tensioning system before elongation readings are started. This preliminary force shall be between 5 and 25 percent of the final jacking force. The initial force shall be measured by a dynamometer or by other approved method, so that its amount can be used as a check against elongation as computed and as measured. Each strand shall be marked prior to final stressing to permit measurement of elongation and to ensure that all anchor wedges set properly. (The latter part is omitted) **10.10.2-Pretensioning Requirements** Stressing shall be accomplished by either single-strand stressing or multiple-strand stressing. The amount of stress to be given to each strand shall be as shown in the contract documents or on the approved working drawings. All strands to be stressed in a group (multiple-strand stressing) shall be brought to a uniform initial tension prior to being given their full pretensioning. The amount of the initial tensioning force shall be within the range specified in Article 10.10.1.4, "Measurement of Stress," and shall be the minimum required to eliminate all slack and to equalize the stresses in the tendons as determined by the Engineer. The amount of this force will be influenced by the length of the casting bed and the size and number of tendons in the group to be tensioned. (The latter part is omitted)
ETA-06/0226 (EOTA 2006b) (Freyssinet International's construction specification)	**E.3.9 Equitension** In the case of a prestressing unit with model C anchorages*, when it is to be ensured that the initial length of each strand is the same prior to tensioning, a pre-tensioning operation can be carried out with the equitension jack†. It has as many tensioning chambers as there are strands to be tensioned, and takes up any slack in the strands individually.

*'Model C anchorages' indicates anchorages for structural prestressing of Freyssient International's system (EOTA 2006b).

†'Equitension jack' indicates initial arrangement jack of Freyssinet International's system (EOTA 2006b).

AASHTO LRFD Bridge Construction Specifications (AASHTO 2017) and construction specification of Freyssinet International (EOTA 2006b) also indicate that equal preliminary tensile forces should be applied to individual strands prior to main tensioning. The purpose of preliminary tensioning defined in the documents is to eliminate initial slack in individual strands. ETC-C (AFCEN 2012) and AASHTO (2017) specify the range of preliminary tensile forces as 5 to 25 % of the final jacking force, and 10 to 15 kN (2.3 to 3.4 kips) per strand, respectively.

ASME CODE CC-4432.5 TENDON INSTALLATION REVISION PROPOSAL

In summary, current ASME Code CC-4432.5 tendon installation requirements bear need for consideration of other preliminary tensioning methods for the following reasons:

1. First, to comply with the requirement to twist all horizontal circumferential tendons, significant work space is required to accommodate installation equipment, including tendon uncoiler and pulling winch. Due to field conditions and construction site limitations, it is almost impossible to twist all horizontal circumferential tendons at the actual construction site efficiently.
2. Second, based on full-scale mockup verification by Domage et al. (2010) and the field experiences by post-tensioning construction companies (for example, Freyssient International), individual strand force deviation using initial arrangement jack can be minimized.
3. Third and finally, post-tensioning-related construction standards and specifications other than the ASME Code do not require twisting of the tendons after installation. Standards and specifications such as ETC-C (AFCEN 2012), AASHTO (2017), and ETA-06-0226 (EOTA 2006b) permit strands to be installed by pulling or pushing individual strands through use of an initial arrangement jack before main tensioning.

Revisions to ASME Code CC-4432.5 tendon installation requirements should consider/include the following:

1. The ability to permit an alternative whereby twisting of all horizontal circumferential tendons may be waived.
2. Waiver conditioned based on the requirement that initial slack of the individual strands is removed by use

of an initial arrangement jack or other proven means.

In light of the aforementioned, proposed revision to existing requirements is shown in Table 6.

CONCLUSIONS

ASME Code CC-4432.5 tendon installation requirement requires that all horizontal circumferential tendons shall be twisted or bundled and pulled into the duct at once to minimize the differential length of individual strands. The deviation of which may adversely affect the strength, ductility, and durability of post-tensioning tendons.

However, compliance during construction is extremely difficult and inefficient. Alternative means and practice to minimize individual strand force deviation by reduction in initial slack through use of an initial arrangement jack is already quite common. Furthermore, established post-tensioning-related standards and specifications exist elsewhere that permit use of an initial arrangement jack in lieu.

Revision to ASME Code CC-4432.5 is proposed based on the field experiences, previous experimental verification on the effect of initial arrangement jack, and relevant standards and specifications established through other publications. The proposed revision includes the following:

1. Twisting all horizontal circumferential tendons may be waived when correction of individual strand force deviation is made using a special device (that is, initial arrangement jack).
2. If the differential length of individual strands can be reduced using the special device, the tendon installation method should not be restricted by the code.

Table 6—Proposed revision of ASME Code CC-4432.5 tendon installation requirements

Current ASME Code (ASME 2019)	Proposed revision
CC-4432.5 Twisting and Coiling	**CC-4432.5 Twisting and Coiling**
(a) Prestressing tendons composed of multiple elements shall be twisted, as necessary, to minimize differential length of the individual prestressing steel elements. Twisting is mandatory for all horizontal circumferential tendons composed of multiple elements stressed simultaneously as a group. The amount of twist shall be specified in the construction procedure. However, intentional twisting of tendons composed of multiple elements stressed simultaneously as a group may be waived for horizontal circumferential tendons as well as other configurations of tendons meeting all other requirements of CC-4430 provided the following additional conditions are met:	(a) Prestressing tendons composed of multiple elements shall be twisted, as necessary, to minimize differential length of the individual prestressing steel elements. Twisting is mandatory for all horizontal circumferential tendons composed of multiple elements stressed simultaneously as a group. The amount of twist shall be specified in the construction procedure. However, intentional twisting of tendons composed of multiple elements stressed simultaneously as a group may be waived for horizontal circumferential tendons as well as other configurations of tendons meeting all other requirements of CC-4430 provided the following additional conditions (1), (2) and (3) are met or that condition (4) is met:
(1) Tendons shall be maximum 0.63 in. (16 mm) strand (ASTM A416) that are prefabricated and pulled into the duct at one time (complete tendon). All strands shall be the same hand lay. (2) Provisions shall be made to keep strands in the tendon bundle parallel as the tendon is pulled into the duct. (3) The uncoiler shall allow individual strands to move against each other as the tendon is pulled in. The tendon shall be pulled from a cage versus being pre-tied and pulled in from a rotating table (lazy susan).	(1) Tendons shall be maximum strands (ASTM A416) that are prefabricated and pulled into the duct at one time (complete tendon). All strands shall be the same hand lay. (2) Provisions shall be made to keep strands in the tendon bundle parallel as the tendon is pulled into the duct. (3) The uncoiler shall allow individual strands to move against each other as the tendon is pulled in. The tendon shall be pulled from a cage versus being pre-tied and pulled in from a rotating table (lazy susan). (4) Tendon strands shall have a maximum diameter of 0.63 in. (16 mm) (ASTM A416). All strands shall be the same hand lay. After the tendon is installed and prior to stressing, each strand of every tendon shall be stressed individually, at the same time, at the same force (up to 10% of the specified strand ultimate strength) with independent individual stroke to remove the slack between the strands.
(b) Coiling, when required for transportation, shall be performed in a manner not to cause damage to the tendon. Coil diameter shall be specified in the construction procedures.	(b) Coiling, when required for transportation, shall be performed in a manner not to cause damage to the tendon. Coil diameter shall be specified in the construction procedures.

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REFERENCES

AASHTO, 2017, *LRFD Bridge Construction Specifications*, fourth edition, American Association of State Highway and Transportation Officials, Washington, DC.

AFCEN, 2012, ETC-C EPR Technical Code for Civil Works, AFCEN, Courbevoie, France.

Cho, K.; Cho, J.-R.; Kim, S. T.; Park, S. Y.; Kim, Y.-J.; and Park, Y.-H., 2016, "Estimation of Prestress Force Distribution in Multi-Strand System of Prestressed Concrete Structures," *Sensors*, V. 16, No. 8.

Domage, J.-B., 2016, "Nuclear Post-Tensioning Activities, Tendon Layout and Risk in Improper Tendon Performance," Presentation, Joint ACI-ASME Committee 359 Meeting, St. Louis, MO, Nov.

Domage, J.-B.; Elias, S.; and Laurens, J.-M., 2010, "State of the Art Post-Tensioning for Nuclear Containments," *Proceedings of the 3rd* fib *International Congress*, Washington, DC.

Domage, J.-B.; Ruffray, N.; and Elias, S., 2013, "Full Scale Post-Tensioning Mock-Up to Illustrate New Technologies for Nuclear Containments," *Proceedings of the Technical Innovation in Nuclear Civil Engineering (TINCE 2013)*, Paris, France.

EOTA, 2006a, "Post-Tensioning Kit for Prestressing of Structures (VSL Post-Tensioning System)," ETA-06/0006, European Organisation for Technical Approvals, Bagneux, France.

EOTA, 2006b, "Post-Tensioning Kit for Prestressing of Structures (System Freyssinet)," ETA-06/0226, European Organisation for Technical Approvals, Bagneux, France.

FHWA, 2013, "Post-Tensioning Tendon Installation and Grouting Manual," Federal Highway Administration, Washington, DC.

Hayek, C., and Kang, T. H.-K., 2017, "Elongation Tolerance for Short Tendons in Post-Tensioned Building Structures," *ACI Structural Journal*, V. 114, No. 4, July-Aug.

Joint ACI-ASME Committee 359, 2019, "ASME Boiler and Pressure Vessel Code, Section III. Rules for Construction of Nuclear Facility Components, Division 2. Code for Concrete Containments," American Society of Mechanical Engineers, New York, NY.

PTI, 2006, "Post-Tensioning Manual," sixth edition, Post-Tensioning Institute, Farmington Hills, MI.

PTI/ASBI, 2012, "Guide Specification for Grouted Post-Tensioning (PTI/ASBI M50.3-12)," Post-Tensioning Institute, Farmington Hills, MI.

VSL, 2010, *The VSL News Magazine*, Issue One, VSL International Ltd., Koniz, Switzerland.

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