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A NOVEL UHPC BASED CONTAINMENT DESIGN METHODOLOGY

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ABSTRACT

In this study, finite element analysis is carried out on an axisymmetric concrete containment model based on a pre-existing nuclear power plant. This model is subjected to factored loads based on ASME Section III, Division 2 Code but with increased load factors for prestress to emulate containment design considering the enhanced compressive capabilities of UHPC. The results show that the required rebar volume decreases as the level of prestress increases, which will reduce rebar congestion and improve constructability. Future phases will involve use of steel fibers to improve the fracture capacity and resistance against impact and impulsive loading, experimental testing of a scaled model, and leak-tightness studies.

INTRODUCTION

Nuclear power plants (NPPs) serve as a reliable source of energy around the globe, but the construction of new concrete containments in the US has been deterred by the schedule delays and cost overruns. The generally high amount of mild steel reinforcement in concrete containments is a notable factor contributing to this issue with regard to required field labor, as well as congestion leading to potential voids within the concrete.

This study explores use of ultra high-performance concrete (UHPC) with steel fibers to relieve rebar requirements for design axial and flexural loads, following procedures laid out by ASME provisions. This will be examined in relation to how the level of prestressing can be increased by utilizing this material in concrete containments. UHPC is defined in ACI 239 as concrete with specified compressive strength at a minimum of 22 ksi (150 MPa) with specified durability, tensile ductility and toughness requirements. The improved compressive strength of UHPC will allow for higher levels of prestressing at service level, while its tensile ductility and strain hardening properties will provide resistance against radial tensile force as well as resistance against impactive and impulsive loading without need for excessive transverse reinforcement.

Rebar design is performed for a pre-existing NPP design with a hemispherical dome, with structural axial and flexural demands determined via finite element analysis, and capacity determined from a modified strength design method laid out in ASME BPVC III-2 Code Case N-850 and detailed by Bae (2011). The level of prestress, denoted as X and expressed as the ratio of prestressing loads to the design pressure load, is changed from 1.0 to 3.0 and the corresponding longitudinal rebar requirements are obtained.

STRUCTURAL ANALYSIS

Analysis Assumptions

Structural analysis was carried out via finite element analysis software DIANA, where concrete was considered to be linear elastic according to Code provisions. The containment configuration was taken from the assumed design, simplified to be axial symmetric and without penetrations or local thickenings. An axisymmetric model was used for gravity loads and design pressure, while the remaining design loads were computed utilizing a 3D model (Fig. 1). The material properties of concrete were determined from NF P18-710 Annex T, which provides indicative values for UHPC to be used at the preliminary design stage. The elastic modulus was assumed to be 55 GPa, Poisson's ratio to be 0.2 and weight density to be 2550 kg/m^3.

The design loads were determined based on ASME Code requirements for primary factored loads. Gravity loads (dead load D and live load L) and design pressure (P_a) were taken from design parameters for the assumed design. Prestressing loads F were implicitly considered as surface pressure, and the level of prestressing is assumed to balance 1.0P_a. After initial rebar design, prestressing corresponding to 1.0P_a through 3.0P_a were considered in performing a parametric study on the relation between level of prestressing and required rebar amount. Because linear analysis was performed, the load factor for prestressing loads was increased instead of performing separate analyses for the increased levels of prestressing.

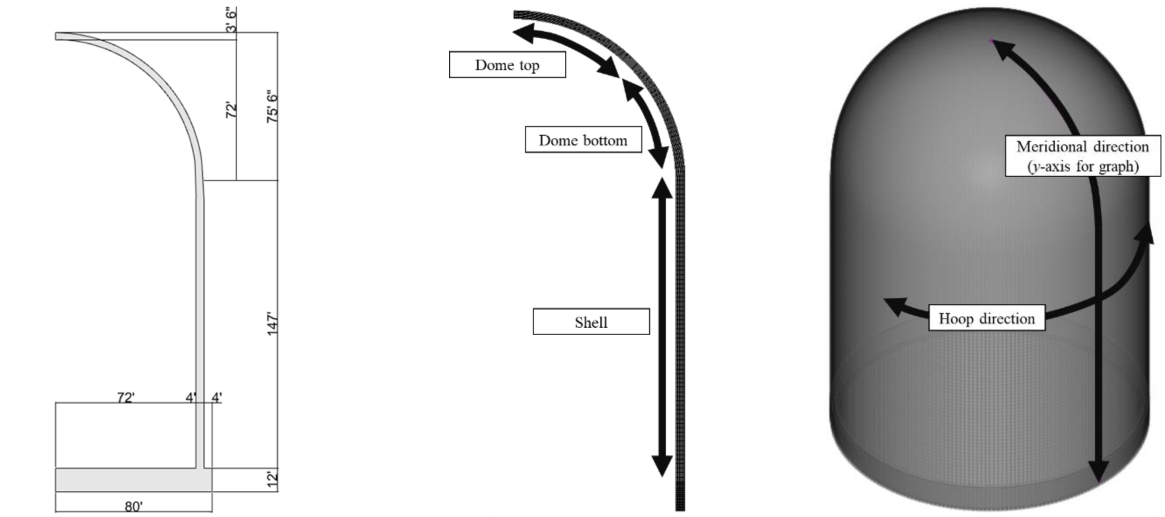
Response spectrum analysis was carried out to determine the seismic load (operating basis earthquake E_o and safe shutdown earthquake E_{ss}), and the peak ground accelerations were taken from the referenced design. Damping values were taken from RG 1.61 while the design response spectra were derived from RG 1.60. As per RG 1.92, modal combination was carried out via CQC and resulting forces in the x, y and z direction were combined through SRSS. Table 1 specifies the design parameters input for analysis. These loads were factored and superposed according to load combinations in ASME Code CC-3230, specifically those used in preliminary rebar design. The load factors for each category are specified in Table 2.

Table 1. Design parameters for structural analysis

Design load		Input values
Dead load (D)		159 pcf (2550 kg/m^3)
Live load (L)		50 psf (2.4 kPa)
Design Pressure (P_a)		54 psi (372 kPa)
Prestressing load (F)	Vertical tendons	300 kip/ft (4378 kN/m)
	Wall hoop tendons	600 kip/ft (8756 kN/m)
	Dome hoop tendons	300 kip/ft (4378 kN/m)
Operating basis earthquake (E_o)	PGA	0.1g (horizontal), 0.065g (vertical)
	Modal damping ratio	0.03
Safe Shutdown Earthquake (E_{ss})	PGA	0.2g (horizontal), 0.13g (vertical)
	Modal damping ratio	0.05

Table 2. Factored load combinations

Category	Load Factors
Abnormal	$1.0D + 1.0L + 1.0F + 1.5P_a$
Abnormal/severe environmental	$1.0D + 1.0L + 1.0F + 1.25P_a + 1.25 E_o$
Abnormal/extreme environmental	$1.0D + 1.0L + 1.0F + 1.0P_a + 1.0 E_{ss}$

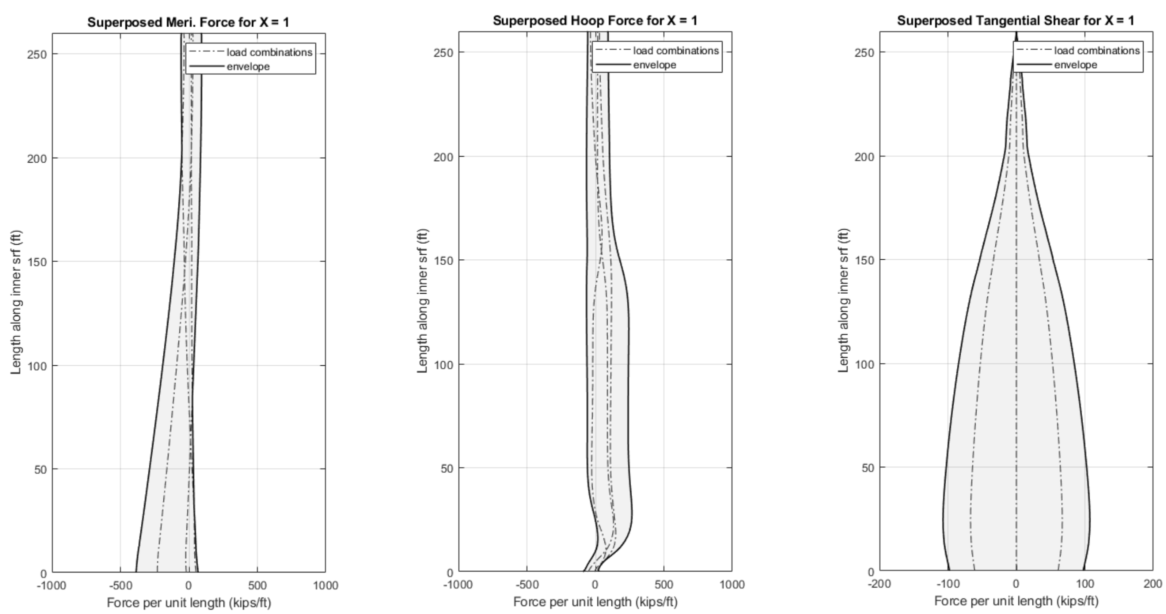


(a) NPP size dimensions (b) Axisymmetric model (c) 3D model

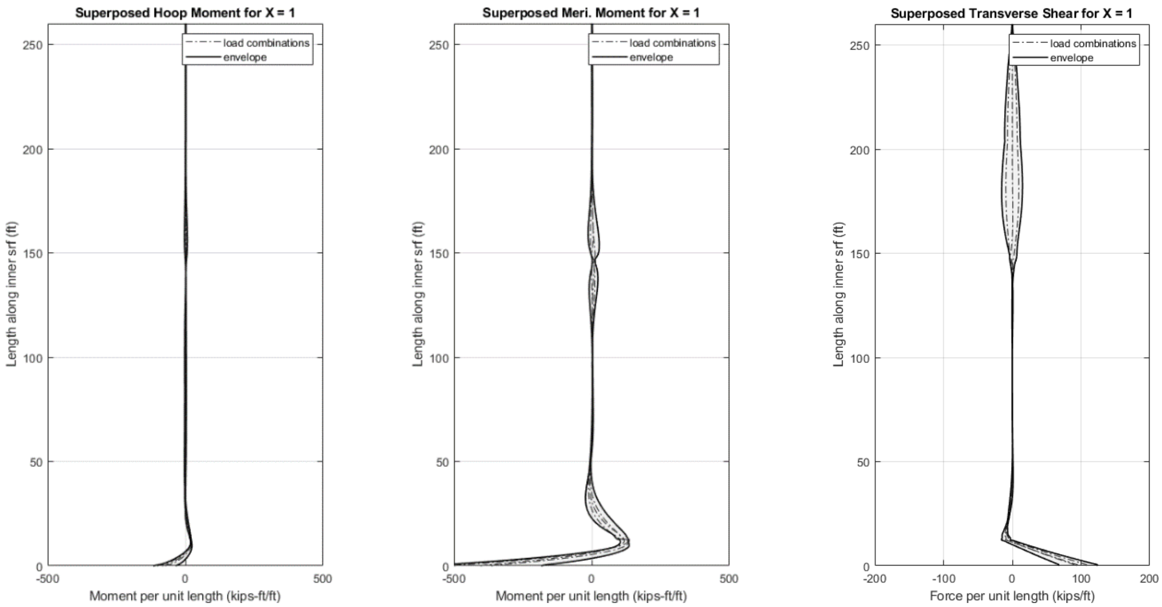
Figure 1. NPP configuration and FEA modeling (Conversion: 1′ = 0.3 m; 1″ = 25.4 mm)

Analysis Results

The resulting factored membrane forces, moments and shear forces are depicted in Fig. 2. Because the level of prestressing was assumed such that it would balance $1.0P_a$ as opposed to the abnormal load with $1.5P_a$, there are areas within the containment wall that are in membrane tension, especially in the shell. The moments along the containment height are prominent near the shell base, to a lesser extent at the springline. While not within the scope of this study, tangential shear is observed to be highest adjacent to the base and is governed by abnormal/extreme environmental loads relating to SSE. Meridional transverse shear is also highest at the base, in this case being governed by abnormal loads. The resulting values for membrane forces and moments served as the structural demands in the design process next section, and levels of prestressing were increased as part of the parametric study.



(a) Hoop force (b) Meridional force (c) Tangential shear



(d) Hoop moment (e) Meridional moment (f) Transverse shear

Figure 2. FEA Analysis results for $X = 1.0$

REBAR DESIGN

Design Assumptions

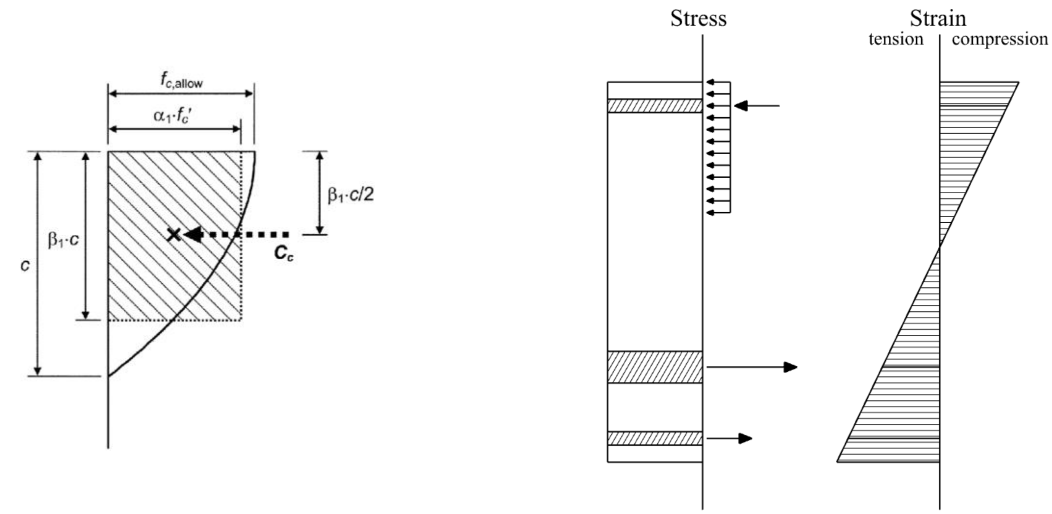
Longitudinal rebar design was performed for 1-ft (0.3-m) wide unit strip of the containment for three sections (shell, dome bottom, dome top), and in the hoop and meridional direction (Fig. 1). Code provisions for axial/flexural loads (CC-3510) were considered. Unlike ACI 349 which references the Ultimate Strength Design (USD) method, ASME Code uses an Allowable Strength Design (ASD) approach to ensure stress and strain at all layers of the sections are within acceptance criteria. However, ASME Code Case N-850 allows for the implementation of USD using modified parameters which are specified in Table 3 to construct an equivalent concrete stress block (Fig. 3(a)). This methodology is further detailed by Bae (2011), and was utilized for this study to visually represent structural capacity and demand on a P-M interaction curve and reduce computational loads.

To obtain thorough insight on how the level of prestressing affects longitudinal rebar design, this paper first compares two approaches in constructing the P-M curve of the containment walls. The first is the natural progression of the initial structural analysis; to regard prestressing as an implicit structural demand and performing conventional RC design. The second approach is to consider prestressing as part of the structural capacity, by disregarding the prestressing demand input and including prestressing steels for the sectional stress-strain compatibility (Fig. 3(b)). After the two methods are compared, a parametric study of the required rebar according to the level of prestressing was performed.

Table 3. Equivalent concrete stress block parameters for ASME Code (Bae, 2011)

	α_1	β_1	ε_{cu}
ACI 318	0.85	0.65 ~ 0.85	0.0030
ASME*	0.60	0.70	0.0013

* Factored loads, primary only



(a) Equivalent concrete stress block (Bae, 2011) (b) Stress-strain compatibility

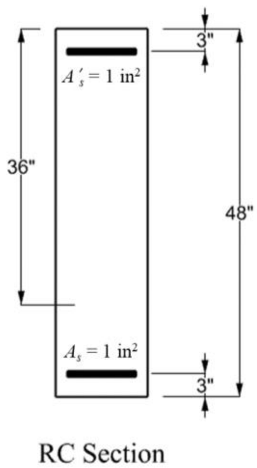
Figure 3. Stress-strain compatibility for P-M curve construction

P-M Interaction Curve and Rebar Design

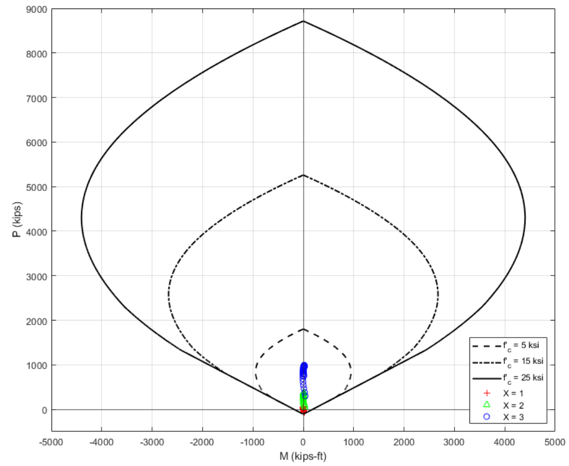
The assumed sectional details and P-M interaction curves for the two methods are shown in Fig. 4. Changes in compressive strength were depicted as different line types for 5 ksi, 15 ksi and 25 ksi (34.5 MPa, 68.9 MPa and 172.4 MPa) while changes in the level of prestressing were depicted as the colors red, green and blue for X = 1, 2 and 3, respectively. The resulting P-M curves considering prestressing as demand in Fig. 4(b) show the abnormal load as the governing load at shell mid height, as a pure tensile demand. Increased levels of prestressing move the demand towards the compression side, which allows the concrete structural capacity to meet the design load demands. Increased compressive strength does not affect rebar requirements for the reinforced concrete (RC) section, as a compressive strength of 5 ksi (34.5 MPa) is already sufficient enough to meet demands at X = 3.

The P-M curves considering prestressing steel as part of the section are depicted in Fig.4(d) and (e), where configurations are different from the RC sections mainly due to the asymmetric tendon placement for hoop tendons. The plastic centroid for calculating sectional moment was determined based on uniform tensile strain for $P < 0$ and on uniform compressive strain for $P > 0$. Structural demand obtained from initial structural analysis was based on linear elastic assumptions and moment was calculated around the midpoint of the wall's thickness, so these values were modified accordingly to maintain consistent assumptions. As with the RC section, the governing design load the abnormal load at the shell mid height, but what was originally pure tensile demand was converted to negative moment around the tensile plastic centroid.

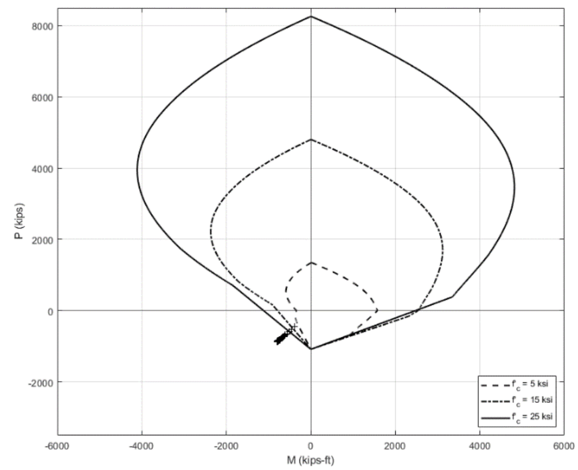
The biggest difference that the second method shows in terms of parametric changes in required rebar is the effect of compressive strength. Because the governing load is not a case of pure tensile demand around the tensile plastic centroid, both concrete compressive strength and prestressing tensile strength act at the corresponding ultimate state, Structural resistance against the governing demand would be most efficiently improved when both compressive strength and level of prestressing are increased. In this regard, the improved compressive strength of UHPC provides direct structural benefits aside from allowing for higher levels of prestressing.



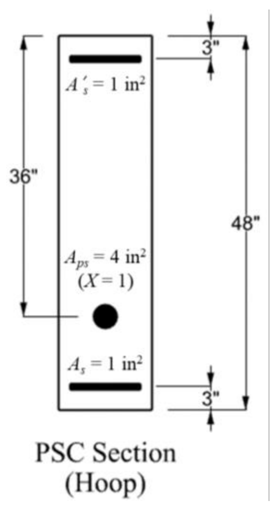
(a) RC sectional details

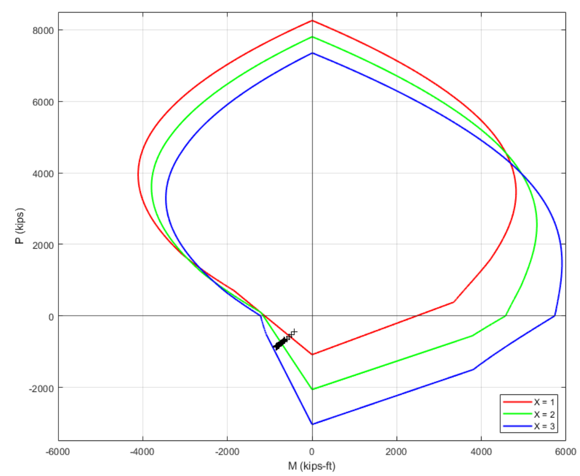


(b) P-M curve for RC according to compressive strength and level of prestressing



(d) P-M curve for prestressed concrete according to compressive strength





(c) Prestressed concrete sectional details

(e) P-M curve for prestressed concrete according to level of prestressing

Figure 4. Parametric study of P-M interaction curves according to sectional assumptions, level of prestressing and compressive strength

For the final quantitative assessment of the required rebar amount according to level of prestressing, the method of considering prestressing as structural capacity for a prestressed concrete section was considered. This method generally provides more conservative requirements, and also considers changes in prestressing strength due to strain variations as well as more accurately depicting tendon eccentricities at ultimate capacity.

The specified compressive strength for this procedure was assumed to be 25 ksi (172.4 MPa), taken from the indicative characteristic compressive strength provided in NF P18-710 Annex T. The level of prestressing was increased from 0.0 to 3.0 by increments of 0.1, and the required rebar area was obtained for each case. This process was repeated for the shell, dome bottom, dome top in the hoop and meridional directions. These required rebar values were averaged across the containment height, and the percentages of required rebar for a containment wall unit volume were obtained and graphically depicted in Fig. 5.

Fig. 5 shows rebar requirements decreasing from 3.67% to 0.19% with the increase in level of prestressing, as a roughly bilinear curve. The decrease in rebar volume is most pronounced for X = 0.0 ~ 1.0, after which the slope decreases. However, because the enhanced compressive strength of UHPC effectively lifts the allowable stress limit of $0.3f'_c$ under service loads, it is possible to increase the level of prestressing to X = 1.0 ~ 3.0, to further reduce rebar volume. With this improvement, requirements will potentially be reduced to a degree where other provisions for serviceability, tangential shear and beyond design-basis accidents would govern the longitudinal rebar requirements.

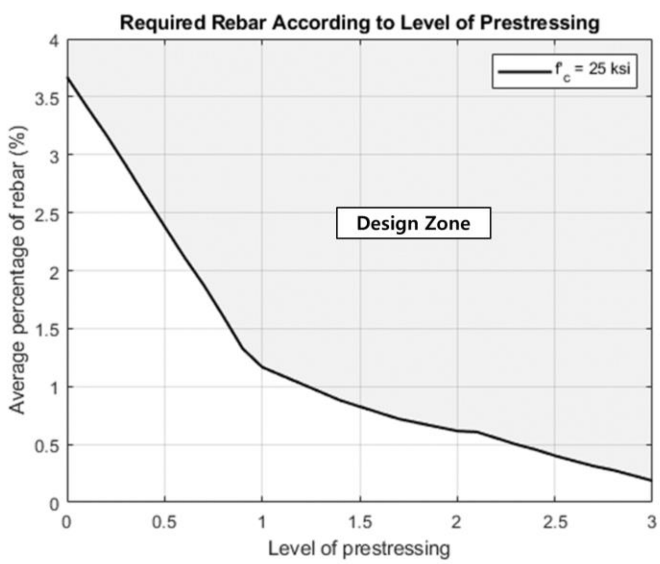


Figure 5. Required rebar percentage according to level of prestressing

CONCLUSION

This study identified UHPC as one method of decreasing required rebars according to ASME provisions, which would decrease construction costs, schedule as well as risk of rebar congestion. A parametric study was performed by increasing the level of prestressing with increase in concrete strength. Structural demand was determined based on finite element analysis on an axisymmetric simplification of an NPP design, and rebar design was carried out according to ASME Code and Code Case N-850.

A study on the methodology for considering prestressing loads was initially performed, by constructing P-M curves for an RC section with prestressing considered as implicit demand and for a prestressed concrete section where the prestressing steel is considered part of the structural capacity in the sectional analysis. In both cases, an increase in prestressing assisted in lowering rebar requirements, but the latter method generally showed more conservative results, as well as requiring an increase in compressive strength along with an increase in prestressing for maximum efficiency. This difference occurs due to the prestressed concrete section being asymmetric for areas with hoop tendons, as the plastic centroid is shifted from the geometric centroid towards the tendon.

To utilize the approach which is both conservative and more beneficial to the actual ultimate capacity, a parametric study for the required rebar volume according to the level of prestressing was performed according to the prestressed concrete sectional design for a specified compressive strength of 25 ksi (172.4 MPa), and results show that longitudinal rebar requirements decrease as the level of prestressing increases. Because the compressive strength of UHPC allows for levels of prestressing beyond the allowable stress limits for normal concrete, it is expected that longitudinal rebar requirements could decrease to the degree where other provisions for serviceability, tangential shear and beyond design-basis accidents would govern. Further studies must be performed in this regard.

Future research will first seek for areas of modification considering UHPC’s strain hardening properties due to added steel fiber, from relevant research and guidelines. Additional considerations for longitudinal rebar used for tangential shear will be considered, as will be radial reinforcement requirements due to transverse shear and radial tension. After a quantitative assessment for containment rebar design with UHPC is carried out, the design’s resistance to beyond design-basis accidents such as impact and impulsive loading will be examined, and further experimental testing of a scaled model and leak-tightness studies will be performed.

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