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Assessment of PCCV axial and flexural load capacity using UHPC design methodology

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ABSTRACT

Nuclear energy is a reliable energy source with low emission, but the industry requires a decrease in plant construction costs in order to retain economic feasibility. The implementation of advanced materials such as ultra-high performance concrete (UHPC) is one facet that could reduce costs (EPRI, 2019). UHPC typically exhibits notable tensile ductility which allows for the consideration of concrete tensile strength in structural design. This characteristic is expected to lower rebar requirements relating to axial and flexural loads, which is typically governed by membrane tensile stress due to design pressure. This study aims to assess the structural capacity of concrete containments implementing UHPC design methodologies to ASME Code provisions.

Design guidelines are taken from French standard NF P 18-710, which presents a consistent and comprehensive design philosophy for UHPC as well as providing indicative values for preliminary structural analyses. A bilinear constitutive law is taken for compressive stress, modified according to ASME allowable limits, and the constitutive law for tensile stress is additionally considered for sectional analysis. P-M curves are generated according to the modified assumptions and compared with curves generated from existing provisions for normal concrete. Possible simplifications to this process are also discussed and topics for future studies are identified.

1. INTRODUCTION

Currently, nuclear energy acts as a prominent source of low-carbon electricity worldwide, which also provides energy security and grid stability (IAEA, 2021). For the industry to retain economic viability, however, decreases in plant construction costs are required. The implementation of advanced cementitious materials such as ultra-high performance concrete (UHPC) is considered to be one potential facet of improvement (EPRI, 2019). In terms of structural performance, UHPC exhibits notable tensile ductility as well as providing long-term durability and impact resistance, which are characteristics that lend to the structural integrity of a prestressed concrete containment vessel (PCCV).

Design codes related to nuclear facilities such as ACI 349 and ACI 359 (otherwise known as ASME BPVC III-2, hereafter ASME Code) disregard the tensile capacity of

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concrete in PCCV design, and ASME Code does not provide guidelines for implementing high performance cementitious materials. However, the enhanced tensile properties of UHPC have garnered worldwide research on methodologies that implement a tensile stress-strain relationship for the design of UHPC structural members (AFNOR, 2016; CSA, 2019; SIA, 2016). This study implements UHPC tensile capacity to pre-established ASME provisions for PCCV axial and flexural design, and investigates the changes in rebar requirements. The French standard NF P18-710 is referenced in this procedure, where indicative values for UHPC analysis, constitutive laws, and sectional design methodologies are provided.

2. AXIAL AND FLEXURAL DESIGN USING UHPC DESIGN METHODOLOGY

In principle, ASME Code provides allowable stress and strain limits for axial and flexural design. An approach which generates P-M interaction curves from equivalent concrete stress blocks is also accepted in Code Case N-850, whose methodology is derived by Bae (2011) based on the aforementioned allowable criteria and sectional stress-strain relationships. The latter approach of obtaining sectional capacity via P-M curves is taken for this study, as to reduce computational load and visually represent the trends of sectional capacity versus demand according to various parameters. Data points for the postulated design loads are obtained by performing finite element analysis for an axisymmetric PCCV configuration with a hemispherical dome, and taking the factored load combinations for primary forces as defined in ASME Code. Prestressing is considered either as structural demand or sectional capacity, where both are expressed in terms of the level of prestressing, denoted as X.

This study generates P-M curves based on concrete compressive and tensile stress blocks, idealized from NF P18-710 design laws. Fig. 1 shows the P-M curves derived from 1) concrete compressive stress blocks only, 2) concrete compressive and tensile stress blocks, and 3) design compressive and tensile laws from NF P18-710. Implementing tensile stress blocks self-evidently results in increased capacity against membrane tensile stress, while also avoiding any knots in the P-M curve that would occur for a tensile law with a descending slope. Fig. 2 shows the typical relation between the governing demand, expressed as membrane tensile stress, and the sectional stress and strain condition which constitutes the corresponding capacity.

Axial and flexural design is performed according to this method, where the required reinforcing steel volume is calculated across a representative unit strip of the PCCV, for 4 segments and 2 directions (Fig. 3). Reinforcing steel layouts are obtained such that P-M curves for prestressing considered as demand and capacity both envelop their respective data points. The result is expressed in terms of the total rebar volume percentage, for X = 0.0 ~ 3.0. Although PCCV design is typically carried out for X = 1.0 ~ 1.5, higher levels of prestressing are considered because the implementation of UHPC may allow for higher tendon forces.

Fig. 4 show the percentage of reinforcing steel requirements for UHPC relative to requirements without consideration of tensile capacity. The domain of X = 1.0 ~ 1.5 show an average rebar reduction of 22.3%, and the maximum efficacy is observed at X = 1.4, where requirements are alleviated by 30.6% with the consideration of tensile capacity. The rebar requirements for X = 1.5 ~ 3.0 show an average reduction of 21%, while those for X = 0.0 ~ 1.0 show the least improvements averaging at 9.5%. However, the latter domain would likely not be considered for PCCV design.

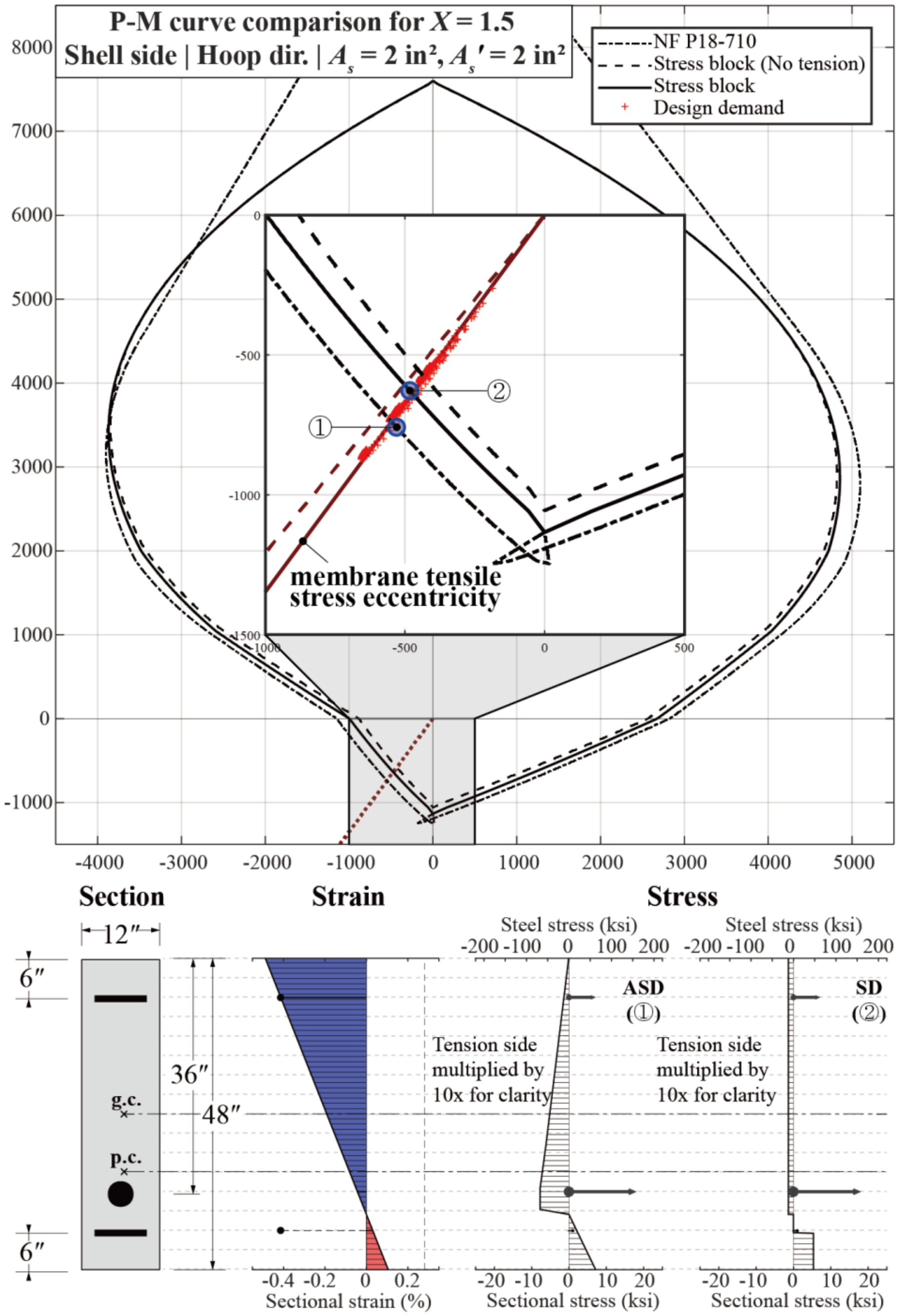

Fig. 1 Comparison of P-M interaction curves according to generation method

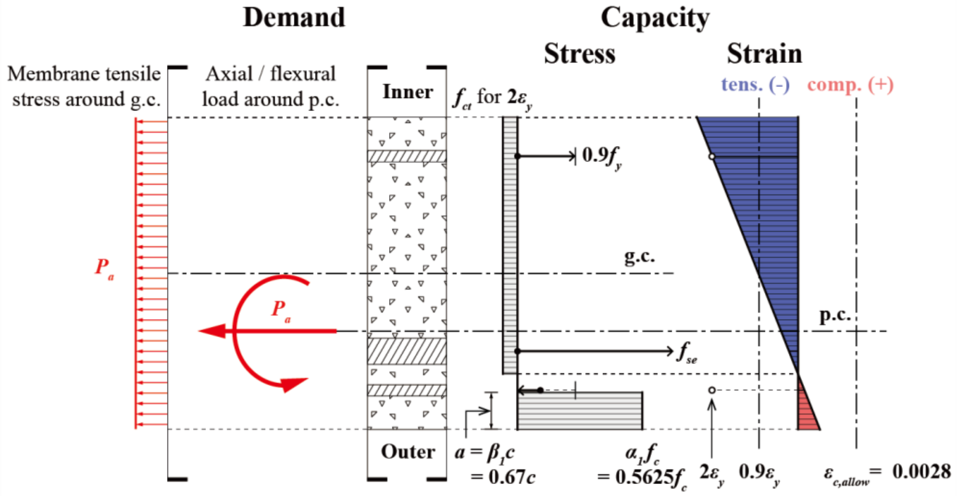

Fig. 2 Relation between governing demand and capacity

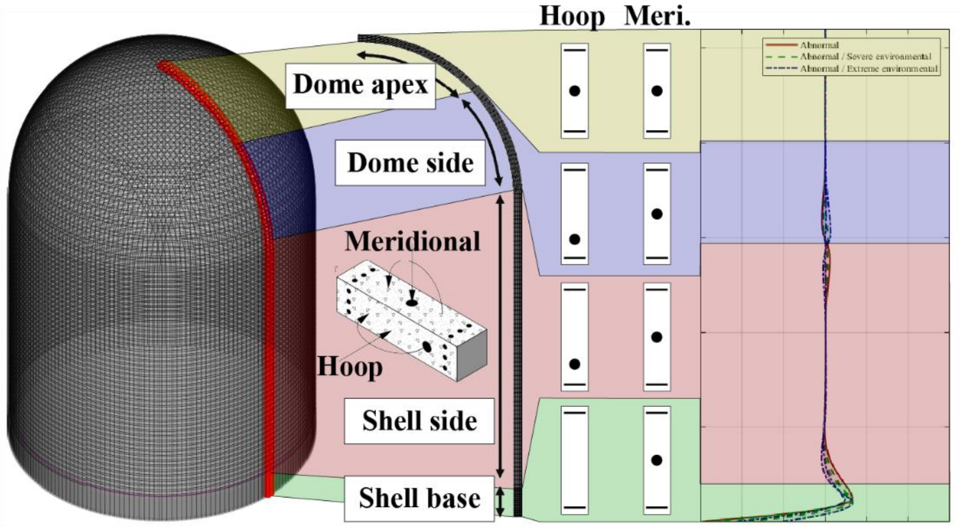

Fig. 3 3D FEA model of PCCV and sectional design assumptions

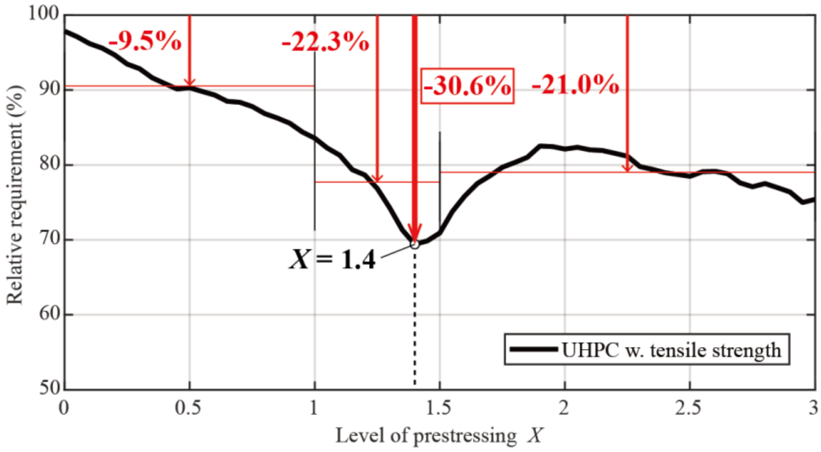

Fig. 4 Relative rebar requirements of UHPC with tensile consideration

3. CONCLUSIONS

This study investigated the effects of implementing UHPC design methodology provided by NF P18-710 into the established ASME Code axial and flexural design. Most notably, the tensile capacity of UHPC is considered due to its notable tensile ductility. P-M interaction curves are generated using concrete compressive and tensile stress blocks. Design results show that rebar requirements are reduced by 22.3% at the typical level of prestressing for PCCV design, with maximum efficacy of 30.6% reduction at $X = 1.4$. Requirements at $X = 1.5 \sim 3.0$ show an average reduction of 21.0%, which demonstrates the increased load capacity at potentially higher levels of prestressing.

Optimizations to this approach may lead to further alleviations, due to the tensile capacity from the stress blocks being significantly more conservative than that of the exact NF P18-710 design laws. In addition, in order to assess the viability of UHPC to PCCVs as a whole, further research on the manifold structural enhancements brought by UHPC is required, regarding items such as tangential shear capacity, radial tensile capacity, long-term durability and impact resistance.

REFERENCES

AFNOR (2016), National Addition to Eurocode 2 – Design of Concrete Structures: Specific Rules for Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC), French Standardization Association, France.

Bae, S.J. (2011), Concrete Stress Block Method for Nuclear Containments, ACI Structural Journal, MI, USA.

CSA (2019), Annex S on Ultra-High Performance Concrete, Canadian Standards Association, Canada.

EPRI (2019), Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction, Electric Power Research Institute, Reston, VA, USA.

IAEA (2021), Nuclear Energy for a Net Zero World, International Atomic Energy Agency, Austria.

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, NY, USA.

SIA (2016), Recommendation: Ultra-High Performance Fibre-Reinforced Cement-based Composites (UHPFRC) Construction Material, Dimensioning, and Application, Swiss Society of Engineers and Architects, Swiss (in Swedish)