Evaluation of Prestressed Concrete Containment with Void

Hyeon-Keun Yang[a*], Jae-Wook Jung[a]
[a]*Structural and Seismic Safety Research Division, Korea Atomic Energy Research Institute, Daejeon, 34057*
[*]*Corresponding author: yanghk@kaeri.re.kr*

Keywords : prestressed concrete, cylindrical wall, void, seismic analysis, finite element analysis

1. Introduction

Nuclear power plants (NPPs) are highly critical infrastructure facilities strictly designed to contain radioactive materials internally, requiring the absolute highest level of structural integrity and durability to prevent leakages during extreme internal or external hazardous events. To satisfy these stringent shielding and performance requirements, the primary structural elements of the containment building—specifically the cylindrical walls—are engineered with massive thicknesses exceeding 1 meter and incorporate heavy reinforcement and tendon ratios of approximately 1%. However, this high-density reinforcement severely obstructs the natural flow of coarse aggregates during the concrete placement process, thereby reducing workability and frequently serving as a primary cause of internal voids and consolidation defects. The regions immediately surrounding large penetrations, such as main equipment hatches and steam piping, are particularly vulnerable due to the heavy congestion of reinforcing bars required to control complex stress concentrations.

The construction of massive reinforced concrete containments in nuclear power plants (NPPs) frequently suffers from localized defects, such as internal voids, due to highly congested reinforcement and concrete consolidation challenges [1]. Authoritative organizations like ORNL and IAEA classify these as primary defects requiring strict non-destructive examination and long-term aging management [2, 3]. Real-world inspections validate this issue, notably at the Hanbit NPP in South Korea, where multiple concrete voids were discovered behind the containment liner plates (CLP) due to inadequate consolidation during initial construction [4]. Furthermore, detecting these defects is a significant technical challenge because containment buildings utilize a steel liner plate (CLP) that acts as permanent internal formwork, rendering visual inspections impossible, while the sheer thickness of the concrete walls severely limits the accuracy of conventional non-destructive testing (NDT) techniques. Consequently, there is an urgent need for a rigorous non-linear finite element analytical approach that explicitly accounts for the geometric characteristics of these internal voids to evaluate localized stress redistribution and macroscopic shear crack propagation accurately.

2. Experimental Background and FE Model Validation

To establish a reliable analytical baseline, this study utilized data from cyclic lateral loading tests previously conducted on reinforced concrete (RC) shear walls containing artificial internal voids. The tested specimens were scaled to a length of 1,500 mm, a height of 1,200 mm, and a thickness of 180 mm, creating a low aspect ratio of 0.8 that represents the shear-critical structural elements typical of nuclear auxiliary buildings. Heavy boundary reinforcement was strategically incorporated to suppress premature flexural failure, isolating the shear-controlled behavior and strength degradation characteristics influenced by internal void sizes ranging from 5% to 20%.

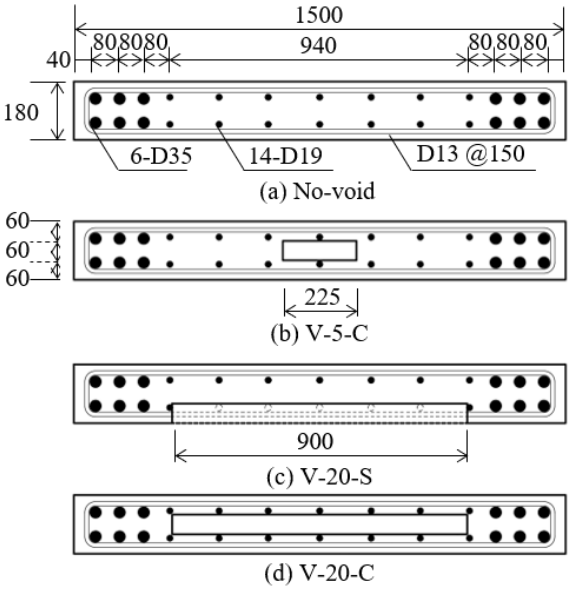


Fig. 1. Cross-section of test specimens

To expand upon these physical component tests, a highly detailed 3D non-linear finite element (FE) model was developed utilizing 50 mm × 50 mm × 30 mm solid concrete elements, employing the Maekawa cracked concrete model for compressive behavior and the JSCE tension softening model for tensile responses. Fig. 2 shows the load-displacement results of test and finite element analysis. This advanced numerical model successfully captured the global structural responses of the void-damaged shear walls, predicting the experimentally measured peak strengths within an

exceptionally narrow 4% error margin across all analyzed specimens. Concrete stress distribution analyses further confirmed that while the intact control specimen developed a uniform compressive stress field along the diagonal strut path, the presence of internal voids severely disrupted the internal shear transfer mechanism by inducing distinct, localized shear stress concentrations around the void peripheries, thereby accelerating damage localization.

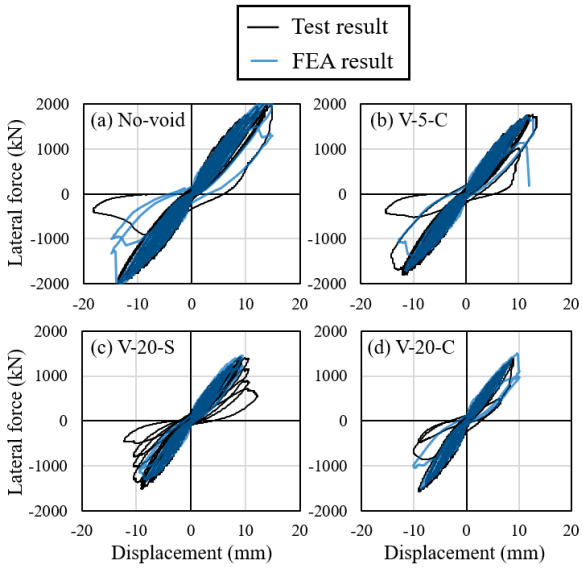


Fig. 2. Comparison of test and FEA results

3.Finite Element Analysis of Containment Building

Leveraging the validated FE framework, a comprehensive parametric analysis was conducted on a full-scale target nuclear containment building based on Lee and Song [5] (OPR1000 YGN 5 and 6). To simulate realistic worst-case operational vulnerabilities, the study introduced geometric penetrations and varying internal void defects specifically positioned beneath the 14-foot diameter main equipment hatch. Fig. 3 shows the analysis model of containment building.

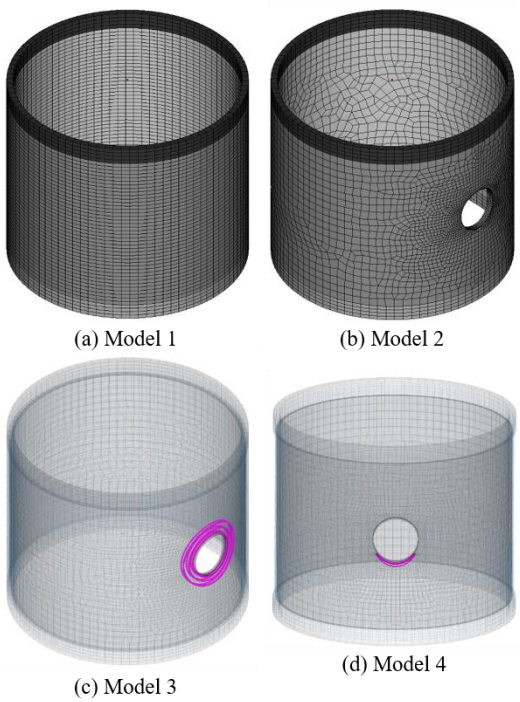


Fig. 3. Finite element model of simplified containment building

Four distinct structural modeling scenarios were evaluated: an intact baseline without penetrations (Model 1), an unreinforced hatch opening (Model 2), a fully reinforced hatch opening adhering to actual design details (Model 3), and three defect models featuring internal voids directly beneath the reinforced hatch with areas equal to 1.0 time the projected hatch opening area (Models 4). The numerical results demonstrated that the maximum shear capacity of the containment structure fluctuated significantly based on the relative incident angle of the lateral loading. Fig. 4 shows the maximum lateral capacity according to loading direction. When loaded along the diagonal shear strut path (angles between 60° and 120°), the unreinforced penetration in Model 2 suffered a severe ultimate strength reduction of up to 48% relative to the intact baseline. However, the dense localized reinforcement surrounding the opening in Model 3 successfully mitigated this degradation, restricting the capacity reduction to only 26%. Regarding the progressive expansion of internal voids, Model 4 exhibited a negligible discrepancy in strength compared to Model 3, indicating that the existing reinforcement effectively mobilized its stress redistribution capacity to bridge the localized defect.

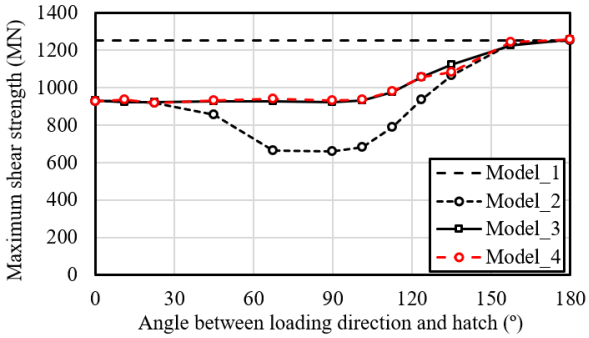


Fig. 4. Variation of maximum shear strength according to loading angle

4. Seismic Fragility Assessment

The probabilistic structural capacities derived from these non-linear FE simulations were utilized to execute a highly refined seismic fragility analysis against a site-specific review earthquake. Because the high-fidelity numerical models eliminated the extreme conservatism inherent in traditional empirical formulations, the epistemic uncertainty factor (β_u) associated with structural strength evaluation was rationally reduced from 0.21 down to 0.15. The other statistical parameters and demand-related values used in the fragility analysis were adopted from Lee and Song [5] and the EPRI guidelines [6]. Consequently, the intact baseline structure (Model 1) achieved a median acceleration capacity (A_m) of 5.53 g and a High Confidence of Low Probability of Failure (HCLPF) capacity of 2.02 g, representing a substantial safety margin increase over conventional evaluations. However, localized cross-sectional loss severely impaired macroscopic fragility; the HCLPF for the unreinforced opening (Model 2) drastically dropped to 1.30 g, while the heavily reinforced design (Model 3) recovered its HCLPF to 1.58 g. Notably, early-stage defect formation equal to the hatch size (Model 4) maintained an equivalent seismic capacity to Model 3, proving that high-density reinforcement initially serves as a robust defense mechanism.

5. Conclusion

In conclusion, while voids that excessively surpass a critical geometric threshold will disrupt primary shear load-transfer paths and undermine structural safety margins, properly detailed localized reinforcement provides a highly effective defense mechanism. Therefore, it can be ultimately concluded that internal voids roughly equivalent to the size of major penetrations can be safely resisted and their structural impacts effectively accommodated by the robust localized reinforcing bars.

ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Climate, Energy & Environment(MCEE) of the Republic of Korea (No. RS-2022-KP002849).

REFERENCES

[1] Heo, Min Beum, et al. "Development of Containment Liner Plate Corrosion Damage Control Technology in Nuclear Power Plant." *Proceedings of the KNS 2018 Fall Meeting*. 2018.

[2] Naus, Dan J., et al. *Aging of concrete containment structures in nuclear power plants*. No. CONF-920541--2. 1992.

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, *Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: Concrete Containment Buildings* , TECDOC Series - 1025, IAEA, Vienna (1998)

[4] Yeom, Yun-Taek, et al. "Containment liner plate void defect detection technique using phased array ultrasonic testing and acoustic resonance method." *Materials* 15.4 (2022): 1330.

[5] Lee, N. H., & Song, K. B. (1999). Seismic capability evaluation of the prestressed/reinforced concrete containment, Yonggwang nuclear power plant Units 5 and 6. *Nuclear engineering and design*, 192(2-3), 189-203.

[6] EPRI (Electric Power Research Institute), *Seismic Fragility and Seismic Margin Guidance for Seismic Probabilistic Risk Assessments*, Electric Power Research Institute, California, Palo Alto, 2018.