

Structural Health and Safety of Nuclear Containments with Innovative Prestressing Systems (SHNIPS)

Bilateral Co-funding R&D Project 2025

1. Project introduction

1.a.1 Motivation:

Nuclear power plants remain a cornerstone of global clean energy infrastructure, with containment structures serving as the ultimate engineered barrier to prevent radioactive release during accident scenarios. Among these, prestressed concrete containment vessels (PCCVs) have emerged as the design of choice, owing to their superior ability to maintain structural integrity and leak-tightness under extreme loading conditions. The continuous compressive stress applied by prestressing tendons mitigates concrete cracking, ensuring robust long-term performance throughout the operational life of the plant.

However, today's global nuclear fleet faces the growing challenge of aging infrastructure. Many units are approaching or have surpassed their original 40-year design life, as operators pursue license renewals extending operation to 60 years and beyond. This trend towards long-term operation (LTO) requires a paradigm shift from traditional curative maintenance — characterized by periodic inspections and reactive repairs — to predictive, proactive approaches capable of detecting and evaluating degradation before safety margins are compromised. Ensuring the continued safe operation of aging facilities demands advanced structural health monitoring (SHM) systems that enable real-time condition assessment, support risk-informed decision-making, and satisfy increasingly rigorous regulatory requirements.

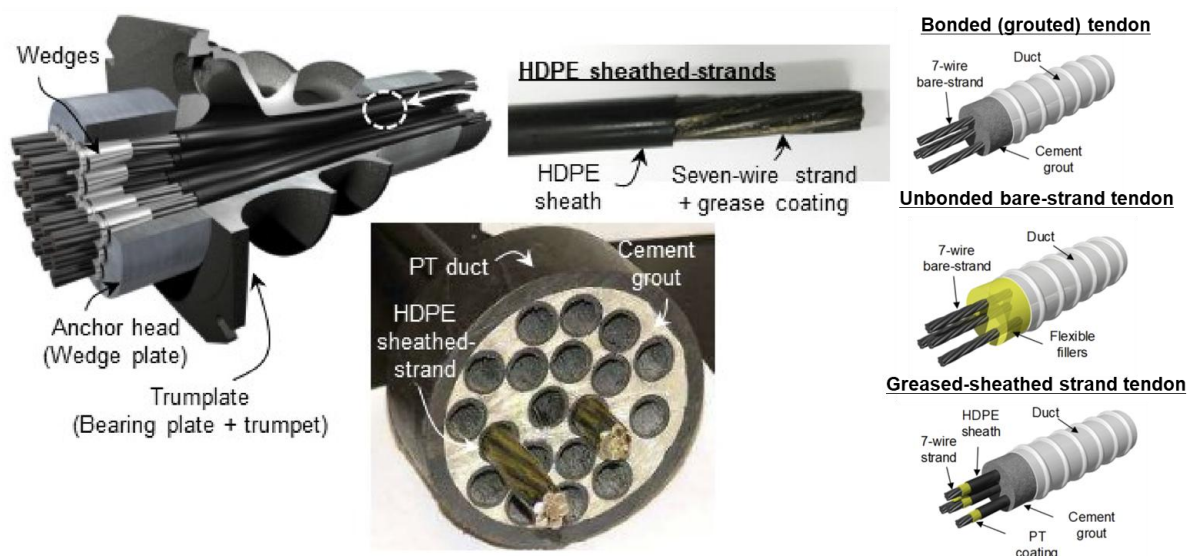


Fig 1.1: Overview of Greased and Sheathed Strand tendon technology (OECD/NEA/CSNI, 2018) (Shin, 2024).

In this context, Greased and Sheathed Strand (GSS) tendon technology offers a promising innovation. Unlike conventional unbonded or grouted tendon systems, GSS technology utilizes individually sheathed strands encased within high-density polyethylene (HDPE) sleeves and lubricated with specialized grease, typically housed within larger ducts that may be optionally grouted. The GSS tendon technology is illustrated in Fig. 1.1 together with other tensioning systems. The GSS configuration offers several compelling advantages:

- Lower friction losses during tensioning, promoting uniform prestress distribution;
- Superior triple-layer corrosion protection (grease, HDPE sheath, and optional grout);
- And most importantly, individual strand-level accessibility for monitoring, detensioning, re-tensioning, and replacement—revolutionizing maintenance practices for aging PCCVs.

These benefits have led to growing international adoption, exemplified by projects such as the Kudankulam Nuclear Power Plant (NPP) Units 1 & 2 in India (Table 1) (Agrawal et al., 2006; Isard et al., 2013). Nevertheless, despite the growing implementation of GSS systems, a critical research gap remains. While the theoretical advantages are well recognized, comprehensive structural performance evaluation methodologies, long-term monitoring strategies, and regulatory frameworks specifically tailored for GSS applications are still lacking. Moreover, systematic long-term performance data remain scarce. This is particularly concerning given the safety-critical role of nuclear containment and the unprecedented service durations now being contemplated.

Table 1. Recent application of GSS tendon in nuclear containments (Shin, 2024).

<i>Country</i>	<i>Name</i>	<i>Reactor Type</i>	<i>Commission Year</i>	<i>Remarks</i>
India	Kudankulam 1&2	VVER-1000	2013 (Unit 1) 2016 (Unit 2)	New construction
Russia	Kalinin 4	VVER-1000	2012	New construction
Russia	Rostov 3&4	VVER-1000	2015 (Unit 3) 2018 (Unit 4)	New construction
Russia	Leningrad II 1&2	VVER-1000	2018 (Unit 1) 2021 (Unit 2)	New construction
Russia	Novovoronezh 5	VVER-1000	1981	Tendon replacement
Russia	Kalinin 1&2	VVER-1000	1985 (Unit 1) 1987 (Unit 2)	Tendon replacement
Russia	Balakovo 1, 2&3	VVER-1000	1986 (Unit 1) 1987 (Unit 2)	Tendon replacement

			1989 (Unit 3)	
Belarus	Astravets 1&2	AES-2006 (VVER-1200)	2021 (Unit 1) 2022 (Unit 2)	Tendon replacement
France	Jules Horowitz	Research reactor	2021	New construction

The very characteristics that make GSS technology attractive—strand-level accessibility, multi-layer protection, and complex material interfaces—introduce new technical challenges for structural health monitoring, degradation assessment, and regulatory oversight. Addressing these challenges is essential to ensure that nuclear containment equipped with GSS systems can reliably fulfil their safety functions throughout their extended service life.

1.a.2 Expertise of the Research Team:

The SHNIPS project brings together a highly qualified international consortium from South Korea and the Czech Republic, combining complementary expertise in design, analysis, assessment, maintenance, and experimental research related to nuclear containment structures. The participating organizations have long-standing experience in both applied industrial projects and cutting-edge academic research directly relevant to the challenges addressed by this project.

Cervenka Consulting s.r.o. (CER) is a global leader in the development of advanced modelling and simulation technologies for reinforced and prestressed concrete structures. The company is the developer of ATENA, a state-of-the-art nonlinear finite element software system for advanced structural analysis of reinforced concrete, which has been widely adopted with over 2,500 installations worldwide. Beyond software development, Cervenka Consulting offers specialized consulting services for the assessment, safety verification, and life extension of critical concrete infrastructure.

Cervenka Consulting has accumulated significant experience in projects directly applicable to nuclear industry needs, including:

- Long-term cooperation with AXPO (Switzerland) for the Beznau Nuclear Power Plant (2011–2025), providing advanced nonlinear modelling services for structural integrity assessment as part of plant-wide stress checks.
- Participation in the HANBIT Nuclear Power Plant (South Korea, 2018–2019), delivering advanced assessments of containment structures.
- Consulting services for AREVA/Framatome during the design of Olkiluoto 3 NPP (Finland, 2005–2008), involving complex modelling and severe accident scenarios verification of containment structures.
- Delamination analysis for the Crystal River NPP (USA, 2010), addressing prestressed containment integrity challenges.
- Extensive participation in national and international research programs, including more than five European projects and ten national projects. Among these, notable contributions include research on severe scenario modelling and long-term structural assessment for the Temelín NPP (Czech Republic, 2017–2025).

The unique capabilities of the ATENA simulation system are illustrated in Figs. 1.2 and 1.3, which present examples from previous projects whose experience and methodologies will be leveraged in the SHNIPS

project. This unique combination of advanced numerical modelling capabilities and practical experience with nuclear facilities positions CER as a key partner for the proposed SHNIPS project.

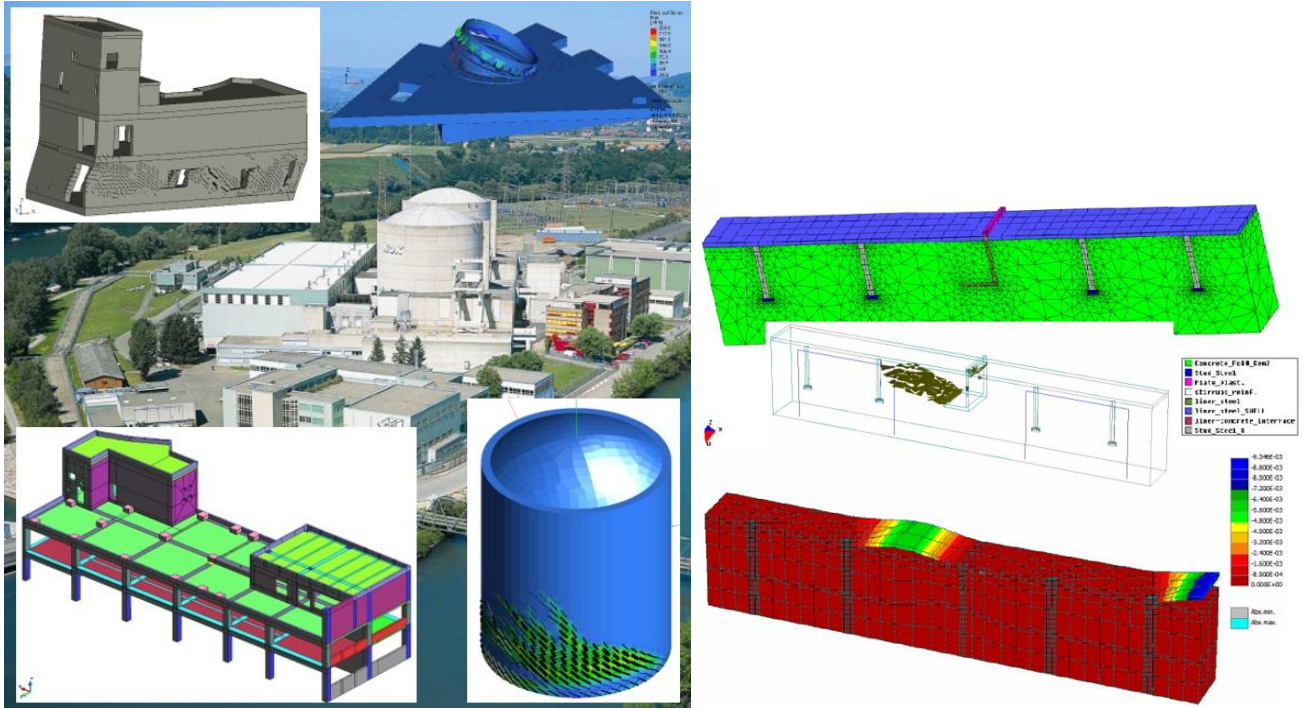


Fig. 1.2: Examples of advanced modelling of critical safety buildings as well as liner modelling and anchoring in NPP (Beznau - Switzerland, Olkiluoto - Finland).

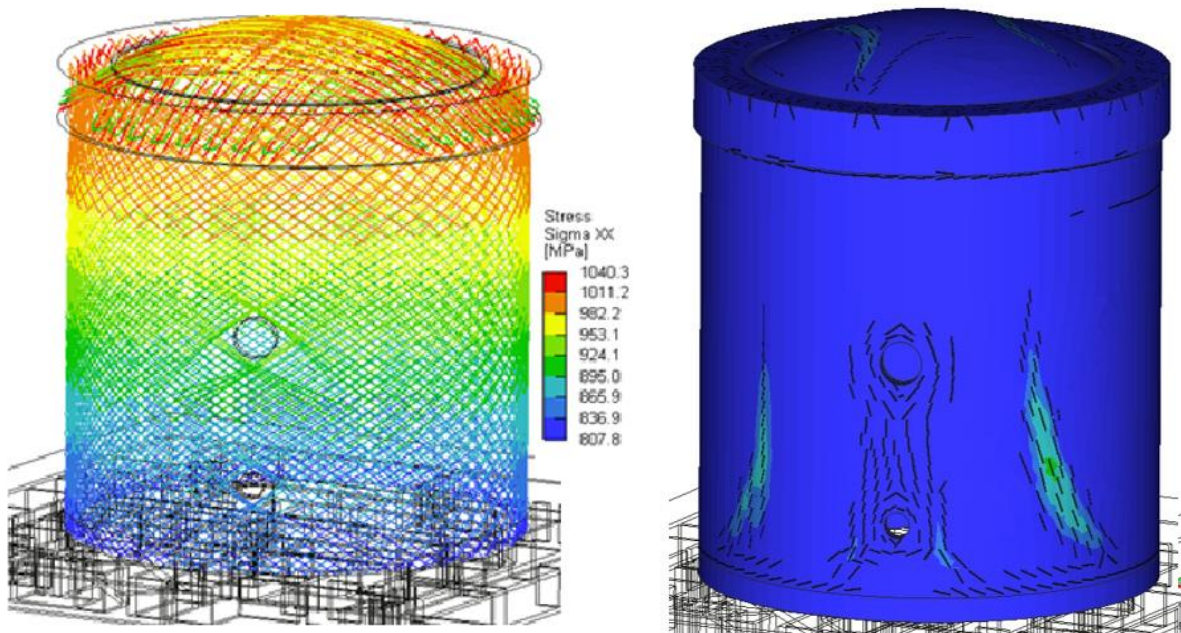


Fig. 1.3: Detailed modelling and stresses in prestressing tendons (left), crack width and pattern during LOCA scenario in nuclear containments.

DAOR E&C (DAOR) is a specialized engineering and construction company that has successfully executed diverse domestic and international projects based on exceptional technical expertise and extensive experience in prestressed concrete structures. As the Korean licensee of VSL International, the company has accumulated extensive construction experience across approximately 200 concrete box girder bridges, over 20 cable bridges, LNG/LPG storage tanks and silos, over 20 large storage structures including nuclear power plant structures, and various building and heavy lifting structures shown in Fig. 1.4. The company has also completed major domestic infrastructure projects including the World Cup Bridge and Godeok Bridge, continuously expanding its technical scope through differentiated construction techniques and quality-focused approaches.



Fig. 1.4: LNG tank project by DAOR E&C Co., Ltd.

Through participation in this research project, DAOR E&C aims to leverage technical collaboration with VSL International to advance into the nuclear plant structure maintenance and monitoring field. VSL International possesses world-class experience and technical expertise in nuclear structure post-tensioning as illustrated in Figs. 1.5, 1.6, making it an ideal partner for advanced nuclear containment research. By combining the company's post-tensioning expertise with VSL's proven nuclear technology and the innovative GSS monitoring framework developed in this project, DAOR E&C seeks to contribute to enhancing the safety, reliability, and maintenance efficiency of both domestic and international nuclear power plant structures.

Completion	Project name	Country	NPP unit	PT*	Filling material	Design	Power	Owner
On-going	Shin-Hanul 3-4	Korea	2	VSL E 6-42	Greased	PWR	1400	KHNP
On-going	Tianwan 7 & 8	China	2	VSL NcU 6-55	PE Greased strands + cement	PWR	1200	CNNC
On-going	Xudapu 3 & 4	China	2	VSL NcU 6-56	PE Greased strands + cement	PWR	1200	CNNC
On-going	Hinckley Point	United Kingdom	2	GPN 55T15	Cement	PWR	1600	EDF/NNB
2023	Zhangzhou 1-2	China	2	VSL Nc6-55	Cement	PWR	1000	CNNC
2023	Saeul 3-4	Korea	2	VSL E 6-42	Greased	PWR	1400	KHNP
2020	Leningrad 2-2	Russia	1	VSL NcU 6-55	PE Greased strands + cement	PWR	1170	Energatom
2019	Barakah 3-4	United Arab Emirates	2	VSL E 6-42	Greased	PWR	1400	ENEC
2018	Leningrad 2-1	Russia	1	VSL NcU 6-55	PE Greased strands + cement	PWR	1170	Energatom
2021	Tianwan 3-4	China	2	VSL Nc 6-55	Cement	PWR	1000	JNPC
2021	Shin Hanul 1-2	Korea	2	VSL E 6-42	Greased	PWR	1400	KHNP
2018	Barakah 1-2	United Arab Emirates	2	VSL E 6-42	Greased	PWR	1400	ENEC
2015	Flamanville 3	France	1	GPN 55T15	Cement	PWR	1600	EDF

Fig. 1.5: VSL International's nuclear power project portfolio.



Fig. 1.6: Representative nuclear power projects by VSL International.

Illustrated in Fig. 1.7, currently, DAOR E&C is conducting research projects to advance the maintenance of nuclear power plant structures, developing core technologies for measuring and calibrating tendon tension and losses, along with associated components such as protective caps. This ongoing work positions DAOR E&C as a valuable industry partner for this GSS tendon research project, bringing practical construction expertise and real-world implementation knowledge to complement the academic research contributions from Seoul National University.

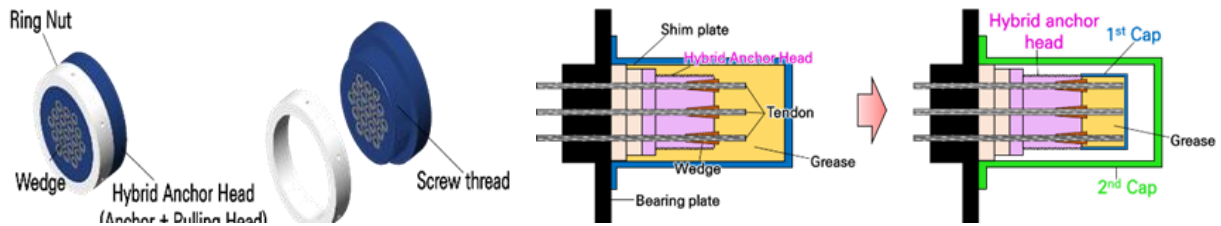


Fig. 1.7: Nuclear power research project currently being conducted by DAOR E&C Co., Ltd.

ÚJV Řež a.s., Czech Republic (UJV), is a leading engineering and research organization in the energy sector with a strong focus on nuclear technology. Its broad portfolio of services covers the entire nuclear fuel cycle, including design and engineering, nuclear safety and reliability analysis, fuel cycle services, technical support for nuclear power plant operation, as well as radioactive waste management and decommissioning. In addition to its nuclear expertise, ÚJV Řež is also active in advanced hydrogen technologies and the development of radiopharmaceuticals.

The Energoprojekt Praha division of ÚJV Řež serves as a general design and engineering office for power plants utilizing a wide range of energy sources, including coal, gas, nuclear, and biomass. With a rich history of participation in major energy infrastructure projects across former Czechoslovakia, Energoprojekt Praha has played a key role in numerous high-profile nuclear and conventional power plant projects. In recent years, it has served as the general designer for the Temelín Units 1 & 2 and the Mochovce Units 1–4 completion projects, while also providing expert support to regulatory authorities involved in international new-build NPP projects.

In preparation for future nuclear development in the Czech Republic, Energoprojekt Praha actively contributes to feasibility and technical studies on Small Modular Reactors (SMRs) and participates in planning and design activities for new nuclear units at the Dukovany and Temelín sites.

With specific reference to the civil engineering aspects of prestressed concrete containment structures, ÚJV Řež provides ongoing technical support to the Temelín NPP operator, focusing on:

- Prestressing system maintenance and inspection (see Fig. 1.8),

- Maintenance and modernization of instrumentation systems for continuous monitoring of deformations and prestressing forces,
- Maintenance of containment airlock systems,
- Periodic evaluation of monitoring and inspection data to verify continued compliance with design and safety requirements.



Fig. 1.8: Maintenance and inspections of prestressing system – lift-off tests and inspection of the tendon removed from the containment after 20 years of operation.

As the general consultant and designer, Energoprojekt Praha provides continuous support for both maintaining and upgrading existing containment designs, ensuring that evolving regulatory and safety standards are consistently met throughout the plant's operational life.

The research team of **Brno University of Technology (BUT)** consists of leading experts in the field of stochastic computational mechanics and reliability engineering of structures. Their expertise ranges from experimental and computational fracture mechanics through structural health monitoring and machine learning-based model updating to deterioration modelling and life cycle assessment.

The BUT team has long been cooperating intensively with partners from academia and industry, including the main Czech applicant Červenka Consulting, through a number of national and international projects. They have been involved in the development of world-renowned software such as FReET (see Fig. 1.9) for statistical, sensitivity, and reliability assessment, its brother software FReET-D for stochastic deterioration modelling and durability assessment, and SARA software for stochastic non-linear analysis of structures. In the development of these tools, emphasis was placed on the ability to "randomize" any engineering computational problem in the sense of Monte Carlo type simulation. The variance of the estimated outputs is reduced by means of a stratified simulation technique, known as Latin hypercube sampling, for a limited number of simulations.

The BUT team has long been involved in advanced load-bearing capacity and reliability assessment of existing prestressed bridge structures, including quantification of uncertainties in prestress losses or degradation modelling and Bayesian updating of service life prediction. Their knowledge and experience are thus an important complement to the project consortium.

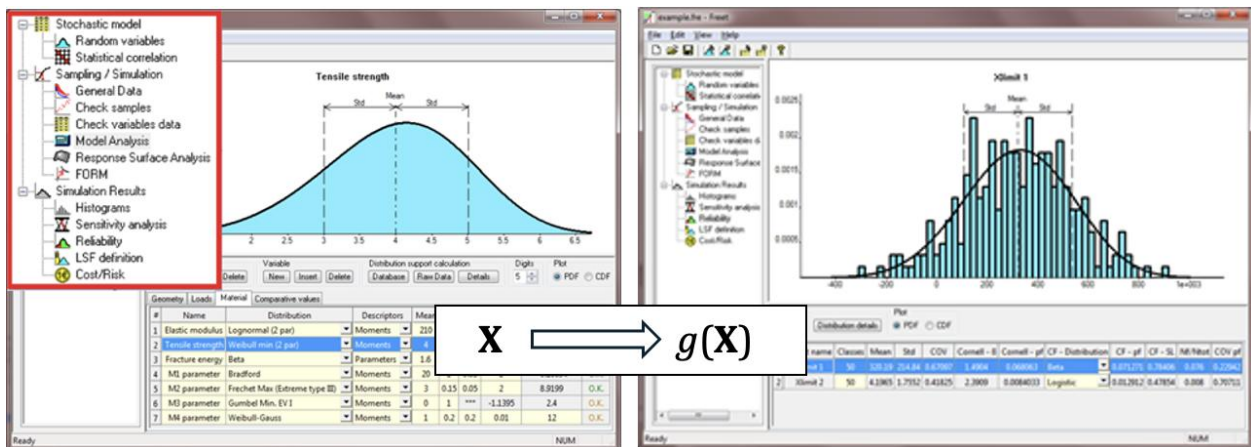


Fig. 1.9: Uncertainties propagation concept in software FReET.

The team led by Professor Kang at **Seoul National University (SNU)** brings world-class expertise in experimental and analytical research on prestressed concrete structures, with particular emphasis on applications within the nuclear sector.

Key contributions from Prof. Kang's group directly relevant to SHNIPS include:

- Full-scale mock-up experiments involving GSS tendon systems shown in Fig. 1.10, where detailed investigations were conducted on tensioning procedures, friction behaviour, and tendon force distributions (Shin et al., 2020). These studies provided critical data used to define installation protocols for GSS tendon systems, which form the basis for the current project's experimental program.
- Research on the development of regulatory guidelines and construction technologies for grouted extruded-strand tendon systems illustrated in Fig. 1.11, addressing key durability and corrosion protection challenges (Yoon et al., 2019). This work has direct relevance for the formulation of new regulatory standards and technical procedures for the innovative GSS systems targeted in SHNIPS.

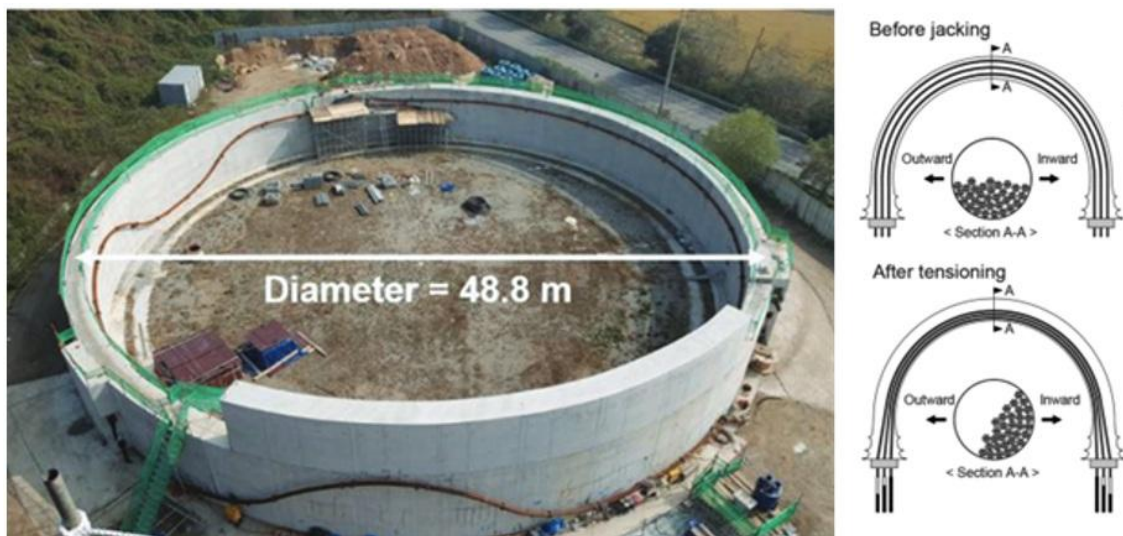


Fig. 1.10: Full-scale mock-up specimen of nuclear containment building.

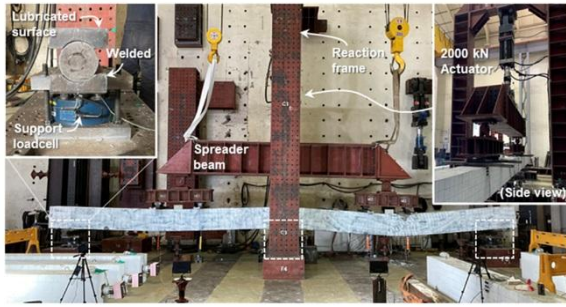


Fig. 1.11: Experimental and analytical program on regulatory guidelines for grouted extruded-strand tendon systems considering durability and corrosion topics in various strand types.

The team led by Professor Jongkwon Choi at **Hongik University (HON)** possesses specialized expertise in experimental research on curved post-tensioned concrete structures and structural health monitoring, with particular emphasis on delamination cracking behaviour and acoustic emission applications. Professor Choi brings significant experience from his previous research, conducting the first experimental investigation of its kind on delamination behaviour of curved post-tensioned concrete structures as shown in Fig 1.12 (Choi et al., 2020). This landmark research involved testing quarter-circle post-tensioned concrete wall assemblies to delamination failure, investigating size effects and aggregate size influences on cracking behaviour, and developing idealized response models.

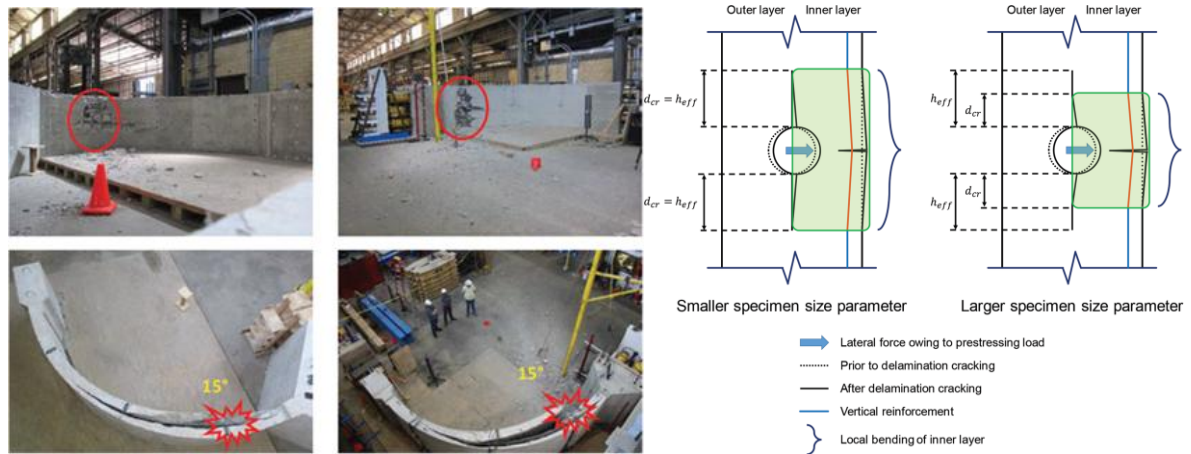


Fig. 1.12: Experimental and idealized response of curved PT wall.

At Hongik University, Professor Choi has performed research focused on integrating acoustic emission technology with machine learning algorithms for concrete structural health monitoring, developing databases for reinforced concrete members and applying automated signal classification techniques based on failure modes as illustrated in Fig. 1.13 (Choi, 2022). The team demonstrates capabilities in large-scale testing, multi-parameter monitoring systems, and advanced data analysis using machine learning algorithms.

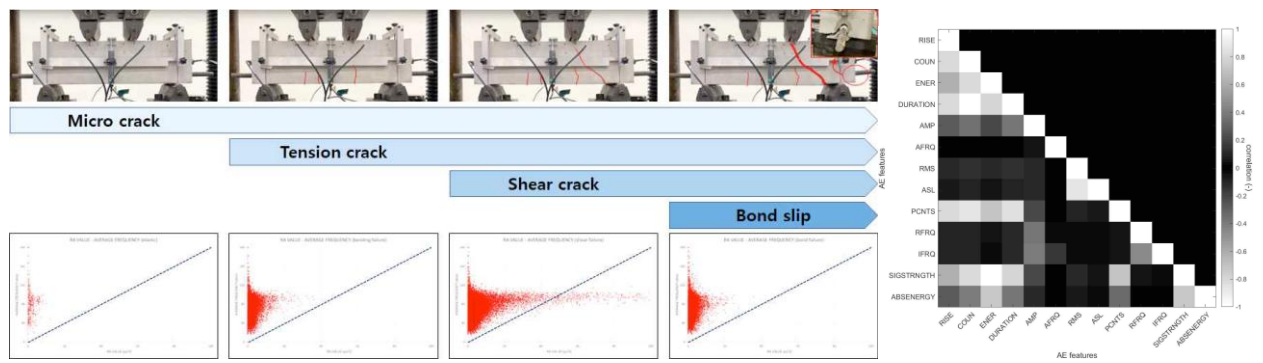


Fig. 1.13: RA value-average frequency analysis of RC beam and correlation analysis of relevant parameters

This expertise is particularly relevant to GSS tendon research through established understanding of delamination mechanisms in curved prestressed structures, behavioural models adaptable for GSS applications, and monitoring methodologies directly applicable to tendon condition assessment. The combination of experimental expertise, acoustic emission capabilities, and machine learning applications positions Hongik University as an essential partner for advancing GSS technology and structural health monitoring in nuclear containment applications.

1.a.3 Project Objectives:

The overarching objective of the SHNIPS project is to develop a comprehensive, long-term framework for the structural health assessment and regulatory oversight of nuclear containment structures employing Greased and Sheathed Strand (GSS) tendon systems. This innovative framework is designed to address the evolving needs of both new-generation nuclear power plants and the long-term operation (LTO) of existing facilities.

The project is particularly timely and relevant in light of the planned construction of up to four new nuclear reactors at the Dukovany and Temelín Nuclear Power Plant sites in the Czech Republic. The strategic partnership between KHNP (Korea Hydro & Nuclear Power) and EDU II has already been formalised with the signing of the contract for the first two reactor units on Dukovany site on June 4, 2025. These developments mark a new era in Czech-Korean collaboration in nuclear energy and highlight the urgent need for advanced structural safety solutions.

GSS tendon technology offers significant advantages for both the design and maintenance of prestressed containment structures, including improved corrosion resistance, strand-level accessibility, and enhanced durability. However, the broader adoption of these systems is currently constrained by limited research, incomplete long-term performance data, and a lack of tailored regulatory and assessment methodologies.

SHNIPS will directly address these gaps by delivering validated tools, monitoring strategies, and safety assessment procedures tailored for GSS systems. These outcomes will support risk-informed decision-making and aging management programs, ensuring the safe and reliable operation of nuclear containments across their full lifecycle — from commissioning through extended operation and decommissioning.

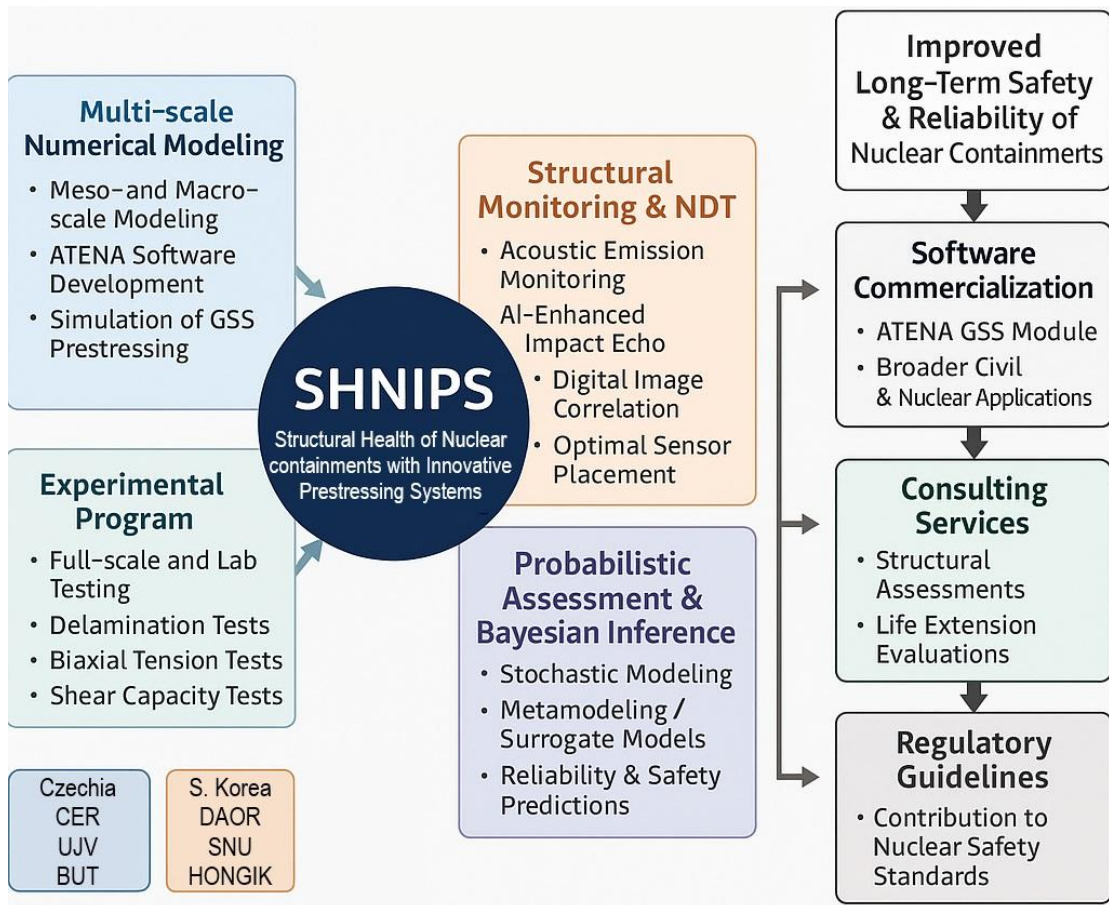


Fig. 1.14: Schematic overview of project key elements and objectives.

To achieve this objective, the project will integrate the following key activities:

Development and Validation of Advanced Numerical Models

Creation of high-fidelity computational models capable of accurately predicting the long-term behaviour of GSS-prestressed concrete containments, incorporating the following complex phenomena:

- Bond-slip relationship of GSS tendons and resulting prestressing losses during the construction and their long-term relationships and behaviour.
- Time-dependent concrete effects: creep, shrinkage, and associated strain redistribution.
- Crack initiation and propagation: microcracking and macrocracking development, particularly in zones adjacent to prestressing tendons and areas subjected to tensile stresses.
- Steel relaxation: long-term loss of prestressing force due to steel relaxation effects.
- Multiscale modelling approach: capturing the structural response from meso-scale (localized behaviour near tendons) to macro-scale (global containment behaviour), supported by appropriate upscaling methodologies.
- Integration and enhancement of numerical models with probabilistic and statistical methods for model updating and reliability predictions.
- Development of AI-based assistants for the numerical model definition and generation.

The numerical models will be tested and validated using experimental results available in the literature as well as reference containment structure large-scale tests based on the Japanese Ohi Unit 3 design, ensuring

realistic modelling conditions and validation against available experimental and operational datasets. The model validation will also be assisted by the extensive experience and large database of monitoring data and acquired knowledge of the partner UJV from the existing Temelín nuclear power plant in the Czech Republic.

Comprehensive Experimental Program

Execution of targeted laboratory tests to characterise the complex stress-strain behaviour and cracking mechanisms in GSS-prestressed concrete containment structures:

- Delamination testing of curved, post-tensioned containment wall specimens to assess interface behaviour under realistic loading scenarios.
- Biaxial tension tests to simulate in-plane tensile stress states representative of accident conditions.
- Shear capacity tests on representative wall segments to evaluate ultimate strength and failure mechanisms.
- Effect of elevated temperatures during severe accident scenarios on structural integrity of post-tensioned concrete panels.
- Investigation of other types of GSS tendons arrangements, i.e. individual without the surrounding duct.

Development and Deployment of Structural Health Management, Monitoring and Non-Destructive Testing Techniques

Design and implementation of advanced structural health management, monitoring systems and non-destructive testing (NDT) methodologies specifically tailored for GSS-prestressed containment structures, including:

- AI-enhanced impact-echo NDT techniques for internal defect detection.
- Acoustic emission monitoring for internal crack detection during detensioning and re-tensioning phases of in-service inspection.
- Non-contact strain measurements using Digital Image Correlation (DIC) for full-field deformation analysis.
- Optimal sensor placement strategies to maximise monitoring coverage, sensitivity, and long-term reliability.
- Probabilistic assessment of structural health and reliability modelling.
- Structural health management and monitoring framework.

This comprehensive approach will provide nuclear operators and regulators with reliable tools to assess, monitor, and manage the structural health of containment structures, ensuring continued safety performance over extended service periods.

1.a.4 Research Activities:

The research and development effort will be organized along the work packages given in Table 2.

Table 2. Summary of the work packages organization.

WP	Name	Task	Description
WP1	Development of advanced modelling strategies for nuclear containment with innovative prestressing systems	Task 1.1	Meso-scale model of critical details near the prestressing strands and ducts, stress and crack development.
		Task 1.2	Modelling of GSS strands, slip, losses, and degradation models
		Task 1.3	Macro-scale model of the containment structure
		Task 1.4	Upscaling and model integration with AI based assistants
WP2	Experimental program	Task 2.1	Delamination test of containment wall quadrant
		Task 2.2	Biaxial tension test of post-tensioned concrete panel
		Task 2.3	Shear capacity test of post-tensioned wall segments
		Task 2.4	Elevated temperature test of post-tensioned concrete panel
WP3	Monitoring and NDT	Task 3.1	AI-based impact echo
		Task 3.2	Acoustic emission monitoring
		Task 3.3	Non-contact digital image correlation
WP4	Structural health assessment and reliability predictions	Task 4.1	Optimal sensor placement strategy
		Task 4.2	Uncertainty quantification and probabilistic reliability assessment
		Task 4.3	Structural health management and monitoring framework
WP5	Coordination and dissemination	Task 5.1	Project coordination
		Task 5.2	Dissemination activities

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