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Content

Page

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Figures

Tables

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1 Introduction

The concrete structures of Koeberg Nuclear Power Station (KNPS) are subjected to atmospheric chloride induced corrosion of the steel reinforcement due to the marine environment of the site. The original design base for the reinforced concrete structures did not adequately consider the chloride as a degradation mechanism and designed the concrete mix to be sulphide resisting.

The chloride induced corrosion occurring at KNPS causes the reinforced concrete structures to degrade through a process called delamination and/or spalling as an effect of the corrosion of the outer steel reinforcement. The corrosion product of the steel reinforcement has a lower density than the reinforcement itself (therefore a greater volume for the same mass). The increase in volume causes tension stresses to develop in the concrete matrix. A mechanical property of concrete is that it has a relatively weak tension resistance (usually ±10% or less of the compression resistance). The concrete releases the tension build up through delamination and/or spalling, which occurs towards the external façade, as the corrosion usually forms on the edge closest to the chloride penetration.

Since construction, chlorides have diffused into the concrete matrix and eventually reached the reinforcement and in the early 2000's on certain parts of the containment structures and it was recommended that a repair strategy be initiated for the structures. Some repairs were carried out and the containment structures were coated. The coating has since failed and was not reinstated. From 2015 to2018 a refurbishment project was initiated, and more extensive repairs were conducted on the delaminating sections of the containment buildings.

Several studies and projects have been completed on the containment structures and there exists a need to document the current position and condition of the containment structures with respect to several aspects of the structures, including planned modifications, current conditions, uncertainties, the planned ILRTs and previous studies conducted.

2 Supporting Clauses

2.1 Scope

The scope of this report is to document the current condition of the containment structures of KNPS and to provide comment on the suitability of the structures for long-term operation (LTO). It looks at several aspects and groups the discussion into the following:

1. Structural Integrity,
2. Monitoring of the Structures, and the
3. Inspection and Repair Regime

2.1.1 Purpose

The purpose of this document is to consider the TLAA conducted as part of the SALTO mission as a basis for the safety case of the containment structures. It looks at the TLAA and validates its findings through the use of state-of-the-art finite element software. It discusses the current condition of the on-line monitoring equipment, the inspection and maintenance programme as well as the upcoming ICCP modification and ILRT.

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2.1.2 Applicability

This document is applicable to Koeberg Nuclear Power Station.

2.1.3 Effective date

Effective once Authorized.

2.2 Normative/Informative References

2.2.1 Normative

[1] D02-ARV-01-183-095: SALTO Koeberg - TLAA 301 Containment Reanalysis

[2] ASME XI: Rules for Inspection of Nuclear Power Plant Components

[3] ISO 9001

2.2.2 Informative

[4] 240-137447723: Technical Requirement Specification for the Design of Impressed Current Cathodic Protection on the Containment Buildings

[5] CE-18279: Containment Online Monitoring System Requirements for its Continued Maintenance and Calibration to be Included in the Current Procedures

[6] CIVIL013: Concrete Baseline Study

[7] JN411-NSE-ESKB-R-5830: Containment Buildings Surface Defects - Numerical Analysis Report

[8] JN426-NSE-ESKB-4988: Deterioration of the Cover Concrete of Containment Buildings

[9] JN465-NSE-ESKB-R-5704: Long Term Repair Strategies for the Containment Buildings - Expert Panel Report

[10] JN876-NSE-ESKB-IR-8818 1HRX: Civil Structure Inspection Report - Containment Building (External) Unit 1

[11] JN868-NSE-ESKB-IR-8760 2HRX: Civil Structure Inspection Report - Containment Building (External) Unit 2

[12] KBA 09 A1C 03 033: Final Report on Prestressing Operations, Containment, Unit 1 and Unit 2

[13] NNR RG-0016: Guidance on the Verification and Validation of Evaluation and Calculation Models used in Safety and Design Analyses

[14] SAR Part II Chapter 1.9.2: Safety Analysis Report - Reactor Building - Containment

2.3 Definitions

None

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2.4 Abbreviations

Abbreviation	Explanation
FE	Finite Element(s)
FEA	Finite Element Analysis
FEM	Finite Element Model
ICCP	Impressed Cathodic Protection
ILRT	Integrated Leak Rate Test
KNPS	Koeberg Nuclear Power Station
LOCA	Loss of Coolant Accident
LTO	Long-Term Operation
NNR	National Nuclear Regulator
SALTO	Safety Aspects of Long-Term Operation
SAR	Safety Analysis Report
TLAA	Time Limiting Aging Analysis
ASME	American Society of Mechanical Engineers

2.5 Roles and Responsibilities

In accordance with Section IWL of ASME XI DIV1 2007 through to 2008 and applicable Eskom procedures, Eskom has appointed a Responsible Engineer.

2.6 Process for Monitoring

N/A

2.7 Related/Supporting Documents

N/A

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3 Containment Structures SALTO Mission

During the SALTO mission, the appointed contractor developed a Time Limited Ageing Analysis (TLAA) [1] for the post-tensioned containment structures to validate the structural integrity of the containment structures of KNPS for long term operation (LTO). The TLAA considered various reports regarding containment measurements and inspections programmes and results which supported the TLAA analysis and conclusion.

The TLAA forms part of the safety case for the LTO of the 1/2 HRX containment structures.

The TLAA references the design criteria of the containment structures when considering the structural integrity of the structures, which is summarized in the KNPS SAR [14] § 5.2.1, specifically that:

"the mean stresses on the thickness of containment remain in compression"

amongst other conditions and criteria.

Furthermore, the TLAA considered three aspects for the LTO of the containment structures, namely:

- Concrete compression and structural integrity, refer to § 3.1
- Functionality of the monitoring system, refer to § 3.2
- Inspections and Repair measures, refer to § 3.3

This report considers these aspects and provides an overview of the Eskom Engineering Position and the suitability of the Containment structures for LTO.

Additionally, other aspects that are important to the safety argument for the containment structures include the:

- Impressed Current Cathodic Protection Modification (ICCP), refer to § 3.4
- The current condition of the structures, refer to § 3.5
- Integrated Leak Rate Test (ILRT), refer to § 3.6

The remaining sections of this chapter provides more details on the topics listed above.

3.1 TLAA - Concrete compression and structural integrity

The TLAA for the containment structures concluded that the structures are validated from a structural integrity point of view.

Additionally, it is important to note that during the TLAA it was assumed that the tendons have not corroded and the TLAA justifies the assumption as valid. Refer to § 3.4 that explores this assumption as well as the planned modification.

The TLAA comprises of various aspects of the containment, including the dome, thickenings, shrinkage and creep, strain etc. and is representative of both Units.

Other aspects that are important for this report are further discussed below.

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3.1.1 Stress Calculations

In the TLAA, the compiler validates the integrity of the structures by considering the stress in the concrete during accident conditions (LOCA) and affirms the design criteria that the concrete stress is required to remain in compression. The TLAA continues to analyse the structure and determines the compression stress in the structure. The results of one of the analyses is summarized below, representing the results of a section on the cylindrical part of containment:

redacted tables are extracts from a 3rd party document. PAIA 37(1).

Figure 1: TLAA result for Dead Loads and Initial Tensioning Stress

redacted tables are extracts from a 3rd party document. PAIA 37(1).

Figure 2: TLAA result for Total Stresses at End-of-Life, including LOCA

The results for the analysis of the cylindrical part of the containment as presented in the TLAA is summarized below:

Table 1: TLAA Results Summary

Condition	Mean Vertical Compression (MPa), Analysis 1 ‘40a’	Mean Vertical Compression (MPa), Analysis 2 ‘40a’	Mean Vertical Compression (MPa), Analysis ‘60a’
Initial Tensioning	7.06	7.06	7.06
End of Life	6.40	5.90	5.70
End of Life and LOCA	2.60	2.00	1.90

These compression values will be compared to a Finite Element Analysis (FEA) conducted by Eskom in § 4.

The TLAA duly considers other sections of the containment structures.

3.1.2 Other Recommendations

The TLAA [1] provides a recommendation for the limit of delamination the containment structures may experience before refurbishment needs to be initiated. The TLAA states that:

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> *"The concrete repair shall latest be performed if a depth of concrete loss of 60 mm is detected over an associated surface area of 25 m². However, if uncovered reinforcement bars are detected by inspection, the concrete repair must be performed immediately and independent from depth of concrete loss and relating surface area."*

To justify the 60 mm depth loss and 25m² surface area limit for delamination the TLAA states that the delamination is not a time dependent parameter as the delamination is local and has a low effect on the long-term concrete compression. The TLAA provides the limits for the loss of depth and delamination area, based on the Contractors' expert opinion and consideration. The TLAA however provides no structural or analytical justification for the 25m² limit.

3.1.3 Eskom Comment

The delamination limit of 25m² surface area is not deemed a feasible or practical value and this report investigates a more reasonable limit. In addition, the recommendation of *immediate repairs* for the spalling or exposing of reinforcement is considered further and is discussed in Section5.1.7.

3.2 Functionality of the monitoring system

The TLAA highlights shortcomings in the condition of the on-line monitoring equipment.

The following recommendations are made in the TLAA:

3.2.1 The number of dome monitoring sensors is at the lower limit and leading to less reliable analysis results than the data for the cylindrical part,

3.2.2 There is a possibility of failure of the remaining functioning strain gauges over the next 20 years (LTO). It is thus recommended to install additional strain gauges fixed to the exterior surface of both domes.

3.2.3 The assumed erratic behaviour of load cell (dynamometer) number 152 shall be observed.

3.2.4 In case of further erratic behaviour of load cell number 152, it is recommended to recalibrate the load cell or to exchange it, if damaged.

3.2.5 It is recommended to perform the outstanding repair of the 4 erratic pendulums in Unit 1.

3.2.6 It is recommended to install additional temperature gauges to improve the temperature monitoring.

3.2.1 Eskom Comment

The Responsible Engineer concurs with the TLAA findings and supports their recommendations made with respect to the monitoring equipment. Eskom is currently addressing the issues relating to the on-line monitoring of the containment structures.

3.3 Inspections and Repair measures

The TLAA concludes as follows regarding the inspection and repair regime followed at KNPS:

3.3.1 The performed inspections and recommended repair measures are deemed sufficient to ensure the structural integrity of the pre-stressed containment structures of unit 1 and unit 2 in the current state. It is recommended to extend the containment surface repairs

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considerably in the following period of LTO to ensure the structural integrity of the containment structures of unit 1 and 2.

3.3.2 The recommendations in the inspection reports shall be followed.

3.3.3 A limit of acceptability for the loss of concrete section area is indicated (25m²). Above this limit, repair measures are mandatory to restore the original concrete section.

3.3.1 Eskom Comment

The Responsible Engineer notes the statement in the TLAA relating to the sufficiency of the inspection regime and repair measures. Additionally, the limit of 25m² is considered and addressed in this report.

The remainder of the conventional maintenance issues that arise through the inspection regime shall follow due Eskom process to address. These include but are not limited to ([7] & [10]):

- Missing down pipes
- Minor hairline cracks at various positions
- Corrosion of various metal components and embedment's

3.4 ICCP Modification

Eskom commissioned a team of local and international experts in 2014-2015 to advise on suitable repair strategies for service life extension of the containment buildings. Their report [7] concluded as follows (amongst others):

3.4.1 The containment structures at KNPS have reached a very advanced state of reinforcement corrosion damage.

3.4.2 Future reinforcement corrosion damage in presently unrepaired areas is expected to develop exponentially with time and result in more widespread delamination.

3.4.3 The end of the operational service life of the containment structures may be reached soon if future corrosion damage is not prevented through application of a long-term repair solution.

3.4.4 The long-term repair solution needs to be able to protect both the reinforcing steel and the post-tensioning ducts from corrosion.

3.4.5 The presently specified patch repair methodology follows state-of-the-art procedures and good practice for localised zones of degradation but will not provide protection to the overall containment structures for the required remaining service life of 40 years.

3.4.6 The only available repair method to meet the defined performance criteria for the containment structures is impressed current cathodic protection (ICCP).

Note specifically Recommendation 3.4.6.

KNPS therefore initiated a modification to implement ICCP on the containment structures. A technical requirement specification was developed [4] for the service and a contractor has been appointed. The design is currently underway and is envisaged to be submitted to the Regulator for their approval in November 2022.

The main function of the ICCP modification is to ensure that the chloride induced corrosion does not affect/ reach the tendons, although it will also prevent corrosion of the external reinforcement.

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The TLAA did not tie the safe LTO of the structures to ICCP and assumed no corrosion has occurred on the tendons. The TLAA states that:

> This approach is based on the assumption that tendons are not corroded and that corrosion is limited to the walls outer rebar layer. The assumption is justified by inspection results described in [2.3.39]. A limited number of tendon ducts were exposed on Unit 2 and some showed signs of corrosion initiation. However, chloride profiles analysis is indicating that the chloride threshold has not been reached at the level of the tendon ducts [2.3.4]. As the tendons are additionally grouted inside the tendon ducts it can be concluded that tendon corrosion has not yet happened.

The TLAA does however note the initiation of the ICCP project and deems the design intent of the project suitable to provide steel corrosion protection in future and states that ICCP should be implemented as soon as possible.

The planned ICCP modification is therefore to ensure the above-mentioned assumption remains valid however is not a functional requirement for LTO.

3.5 Current Condition

3.5.1 Behaviour of Patch Repaired Areas

As noted, the structures' reinforcement is currently subjected to active corrosion due to chloride induced corrosion of the external reinforcement. Eskom implemented patch repairs, in accordance with approved specifications (e.g., DSG-318-208). A patch repair replaces the corroding anodic area with a cathode by replacing the contaminated and delaminated concrete with a new uncontaminated material (free of chlorides).

In the absence of ICCP, the anodic area displaces towards the edge of the patch repair, which causes new delamination to form adjacent to the repaired area. In an effort to mitigate this behaviour, the repair specification calls for galvanic sacrificial anodes to be placed on the periphery of the repaired areas, and the latest inspection report indicates this repair methodology is handling phenomena relatively well [10], however not with 100% effectiveness. A cycle therefore can develop where a repaired area can accelerate delamination in the adjacent, previously intact concrete.

A sound case is therefore made that the delamination and repair regime should be carefully managed to minimize the impact on the containment structures, and to ensure that minimum invasive work is conducted prior to the installation of ICCP, as ICCP's design intent is to mitigate chloride induced corrosion and the aforementioned affect.

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Furthermore, the ICCP Contractor has highlighted risks relating to the current repair specification and the possibility that the repair specification might have some negative consequences regarding the compatibility with ICCP (related to discontinuities in the electrical properties of the structure when new repair material is added to the existing building). This risk, although minor, will be duly considered prior to installation of ICCP.

3.5.2 Delamination

As part of the inspection regime of the containment structures, delamination surveys are conducted to determine the extent of the delamination at the time of the inspection. The latest results are summarized in Table 2, along with an overview of the previous repair project's extent of repairs.

Table 2: Historic and Current Delamination Status

Current Condition	1 HRX	2 HRX
Total Area Repaired (Previous Round)	445 m²	498 m²
Years Since Previous Round	4	5
Delamination Since Previous Round	46 m²	43.2 m²
Delamination per year	12 m² / year	8.6 m²/ year

Furthermore, it is noted that the previous successful ILRTs conducted in 2015, were conducted with degradation in the structures and no structural integrity concerns were identified.

3.5.3 Chloride Profiles

For the 2HRX inspection during 225, core samples were taken from the structure to conduct chloride profile analyses. The new chloride profiles (of 2022) were compared to results from 2014 and 2018. The inspection report concluded that:

"Chloride contamination has increased slightly over the past 8 years, although the values obtained in 2022 are generally similar to those obtained in 2014 (and 2018). This results in an increasing risk of corrosion of the reinforcing steel and prestressing ducts, in non-repaired areas.

The delamination survey indicates that the anodes inside the repair patches have generally been successful in preventing widespread reinforcement corrosion around the patch repairs. Some new delaminations have occurred in isolated regions. This, too, results in an increasing risk of corrosion of the reinforcing steel and prestressing ducts, in non-repaired areas.

In general, the additional information from the containment outage inspections in 2022 has not resulted in any additional information that impacts on the life prediction model of the containment structures. However, the data obtained confirms the need for installation of impressed current cathodic protection (ICCP) remains an important factor for the long-term integrity of the containment structures."

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3.5.4 Tendon Condition

It is noted that the tendons form the core of the structural strength of the structures. As such the TLAA [1], previous numeric analysis [7] and Section 5.1 of this report carefully considers the tendons.

Furthermore, previous investigations conducted by Eskom and his appointed Inspector [8] indicated that, in general, the tendon ducts were in good condition at the time.

3.6 ILRT

An integrated leak rate test (ILRT) is a full-scale functional test to confirm the integrity of the containment structures by replicating the conditions of a loss-of coolant accident (LOCA). The test includes increasing the pressure inside the containment structures to 400 kPa.

The ILRT (and associated Structural Integrity Test (SIT)) is a method to determine the functional behaviour of the containment structures and can be used to provide confidence in the structural integrity of the structures, i.e., if any concerns exist, an ILRT shall confirm the behaviour of the structures under LOCA pressures and mitigates the risk of uncertainty that may exist for the short term from when the ILRT was performed.

The previous ILRTs (2015) confirmed elastic behaviour and structural integrity of both 1HRX and 2HRX.

ILRTs are performed 10-yearly in accordance with in-service inspection requirements and the next planned ILRTs was planned for outages X27. It was however decided that if the ILRTs were to be conducted in X26, it would give KNPS sufficient time to mitigate risks. It was subsequently decided that the ILRT may be moved to X26 to mitigate these risks, which include

1) LTO risks,
2) provide KNPS with time to solve issues that may exist, and to
3) provide KNPS with sufficient time to develop the safety case.

The following was presented to management during a senior review board meeting:

> *"By the time that the LTO Safety Case is due in 2022, Koeberg will not meet all the NNR requirements for ageing management to provide confidence of the long-term integrity of the containment civil structures. It is likely that this situation will remain at 40 years of operation. Before the expiration of the current license variation therefore, Koeberg will have to provide a Justification for Continued Operation to exceed 40 years. Successful ILRT results on the containment buildings are required before 40 years (in X26 Outages) to provide confidence of containment integrity in the short term."*
>
> *"This strategy provides Koeberg with improved arguments for exceeding 40 years operation (in the short-term) while actions to achieve the remainder of the NNR ageing management requirements are due."*

It is reiterated that the ILRTs will confirm structural integrity of containment structures, however there are no statutory requirements to perform the ILRTs during x26. Therefore the ILRT might be moved back to x27 to mitigate other organizational risks.

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4 Structural Integrity Analysis

The TLAA was conducted by external appointed Contractors. Eskom has in the past commissioned other external Consultants to conduct analyses on the delaminated state of the Containment Structures. A structural finite element analysis was subsequently conducted and showed that the 2HRX structure's integrity, even in a degraded state (with 63m² delamination), is not impacted such that it cannot meet its design base requirements [7].

Eskom developed a third analysis to do an in-depth analysis of the delamination of the cylindrical part of the containment structures, to determine the effect of the delamination, as well as to determine a practical limit for the allowable delamination which the Responsible Engineer will deem acceptable. This section discusses this analysis.

4.1 Finite Element Model

A simplified finite element analysis ¼-symmetry model was developed for a representative containment structure to determine the effects different conditions would have on the structure.. The ¼-symmetry model was used to minimize computing time, provide more control over the analysis and to represent both units. The use of symmetry in FEM is standard practice when conducting FEA.

The model is representative in dimensions, thickness, vertical tensioning and concrete strength of the containment structures. No penetrations, reinforcement, horizontal tensioning or dome tensioning was considered. The dome and horizontal tensioning were excluded as justified in § 4.2.1. No other structural aspects were included such as internal structures, the raft foundation or the liner.

ANSYS 2021 R1 was used for the analysis - refer to § 4.6 for further information on ANSYS.

The ANSYS SpaceClaim model of the structure is shown in Figure 3. Note the areas created on the cylindrical section of the walls which will represent delamination areas.

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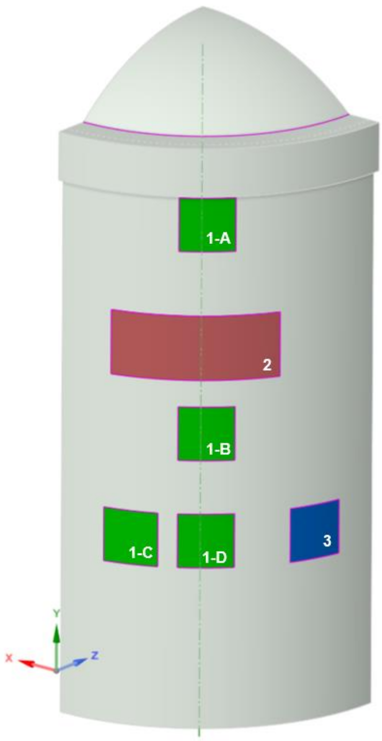

Figure 3: ANSYS ¼ Model of a Containment Structure

The total cylindrical wall modelled is **966 m²** in surface area and **1,352 m³** in volume.

For the analysis, 6 areas were created that represents the delamination or patch repairs. These areas represent 3 different patches, namely:

1. Four (4) 5 m × 5 m × 70 mm patches, represented in green
2. One (1) 15 m × 6 m × 70 mm patch represented in maroon
3. One (1) 5 m × 5 m × 120 mm patch represented in blue

The total area of delaminated concrete modelled is **±215 m²** (22% of total area) which represents **±16.6 m³** (1.2% of total volume). For reference, during the previous repair project, an estimated 11% of the structure's surfaces was repaired. Additionally, as the analysis makes use of ¼ symmetry, it can be inferred that 215 m² × 4 is modelled in total on the cylindrical part of the containment structure, i.e., **860 m².**

In the analysis, several results were monitored, including the compression stress through the thickness of the concrete, radially in the middle of 'Patch 1-B'.

Note that the patches/ areas above can also represent areas that have already been repaired. As the concrete is in compression due to the tensioning of the tendons, the force will be shown to redistribute around the delaminated area. If concrete is replaced in this area, this concrete will not be in compression, and the redistribution will not reverse.

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4.2 Finite Element Analysis

The analysis was conducted stepwise, after the initial development of the geometry, and included modelling the systematic events affecting the structure, as defined below:

Step 1. Tensioning the tendons to the original/ initial tensioning load was applied through defining the top and bottom positions of the vertical tendons and adding prestress values to a beam element representing the tendons. The model considers 53 vertical tendons,

Step 2. Once the prestressing was applied, the stress was reduced, which represents the relaxation of the tendons over 60-years, to a mean value, determined through the TLAA report,

Step 3. Thereafter, areas representing patches (Figure 3) were identified and the elements were deleted or removed from the analysis to allow the prestressed analysis to redistribute. Firstly the elements representing 'Patch 2' was removed to determine the effect of the loss of one big patch,

Step 4. Next, all of the remaining patches were modelled by removing the elements representing the delaminated areas. The analysis up until this point is the current and expected conditions on the containment structures,

Step 5. As an additional check, this step allowed the prestressing on a cable to reduce to zero, which represents the complete loss of a cable, i.e., a cable to snap,

Step 6. Finally, a LOCA pressure of 400 kPa is modelled to determine the structural integrity of the containment structures in the expected state of delamination and the imaginable state of a snapped tendon.

The results of Step 1, Step 2 and Step 6 could then be used to compare the results to the TLAA, although the TLAA did not include the loss of a tendon in the analysis.

Note that a LOCA is used for the reference accident analysis in accordance with the SAR [14] § 4.8.

4.2.1 Exclusion of Dome and Horizontal Tensioning

The containment structures of KNPS are post-tensioned with tendons, consisting of 19 cables and each cable consisting of 7 strands of 5 mm each. The tendons are encased in ducts which were grouted during the construction activities of KNPS. An illustration of the cross section of a tendon and all its associated components is given in Figure 4.

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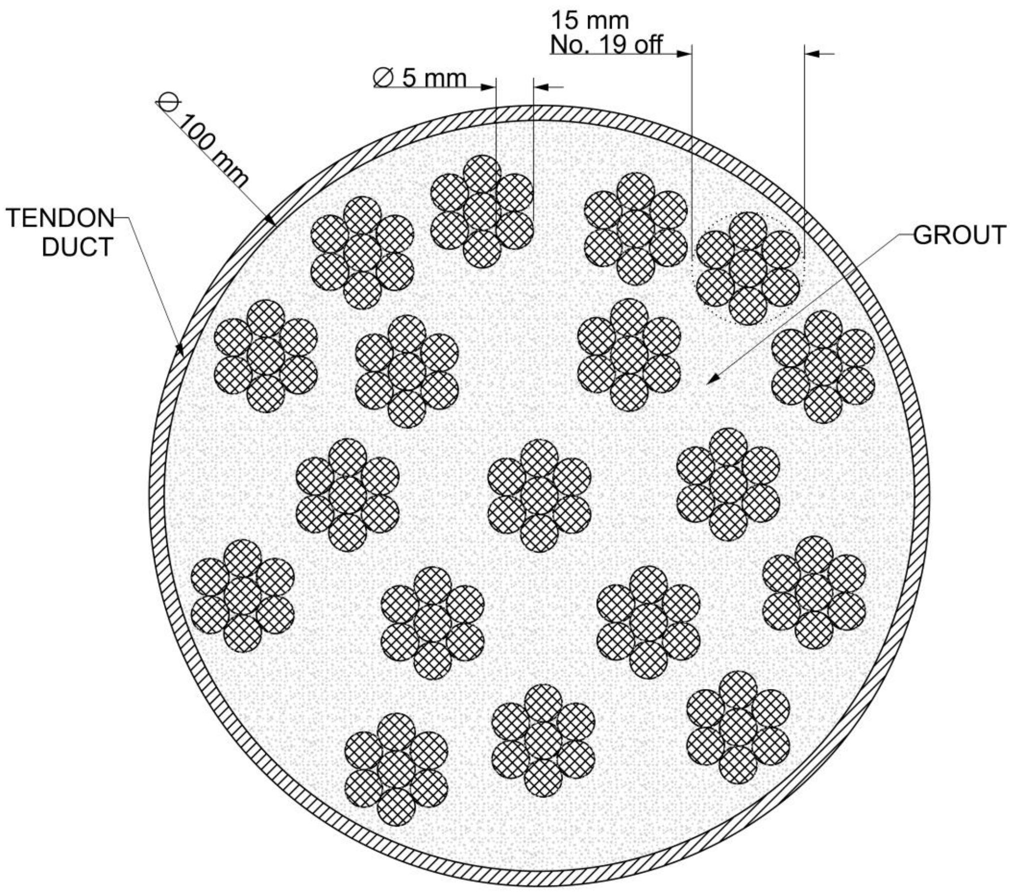

Figure 4: Schematic of Tendon Cross Section

NOTE: The actual location of the cables inside the duct is not representative of site conditions.

The tendons can be divided into three groups with distinctly different orientations, namely:

- Vertical tendons in the cylindrical part of Containment,
  - The vertical post tensioning of the cylinder is made up from 216 cables which are rectilinear along the shell. The cables are placed at a cylindrical raids of 19.13 m. The inter-cable space is approximately 550 mm. These cables extend at their lower end into the aseismic vault (the area between the lower and upper raft). These cables are tensioned from either of the two extremities § 2.6 [14].
- Horizontal tendons placed around the circumference of the cylindrical part of containment
  - The horizontal post tensioning of the cylinder is made up from 255 three quarter turn hoops whose anchorage are embedded in four vertical ribs. The cables are placed in two layers which are on cylindrical radii of 19.03 and 19.23 m. The inter cable space (measured between the axes of the conduits) is in the standard part of 200 mm. The cables are tightened simultaneously from both ends § 2.6 [14], and
- Dome Tendons placed in a special configuration across the dome

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- Post tensioning of the dome is done by 162 cables grouped into three families having 60º angles between them. Each cable in the standard part is found in a spherical span of radius (24.38 m; 24.48 m; 24.58 m) in a hemispherical layout. A counter radius that runs on a ring enables connection to the standard part with the anchorage embedded in the ring beam. These cables get tensioned simultaneously from both ends § 2.6 [14].

For the horizontal and dome tendons, the geometry is radial, that is, placed at a radius along a distance. The implication of the radial placement of the tendons, and then tensioning the cables, is that the tensile force of the cable is transferred to the concrete through a uniformly distributed radial force.

This is illustrated in Figure 5 for the horizontal tendons in the cylindrical wall of containment.

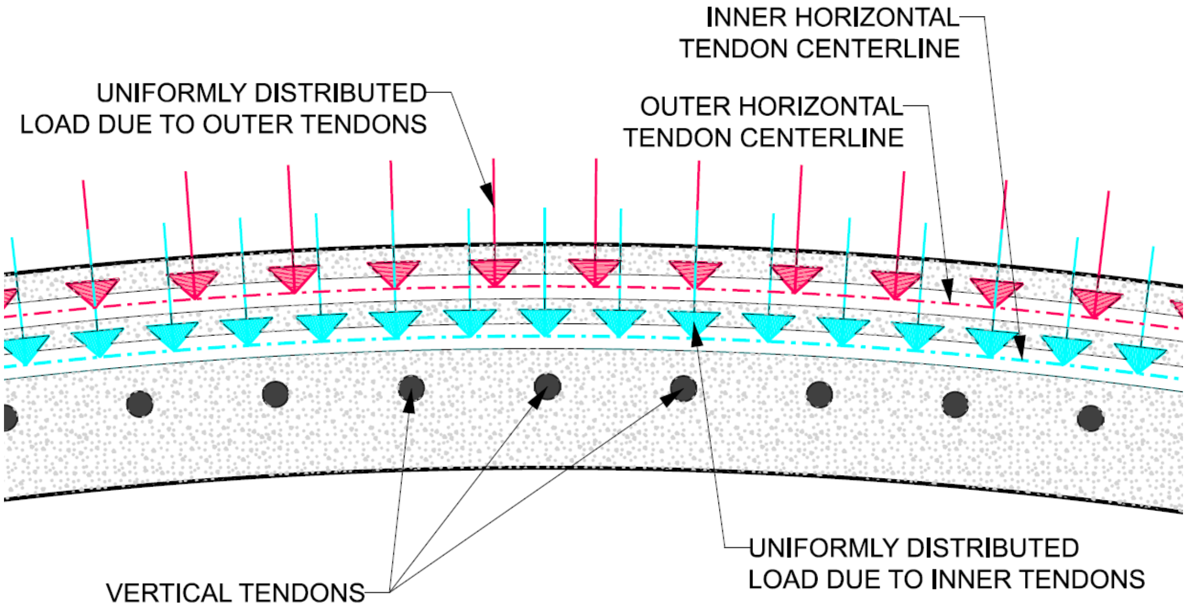

Figure 5: Cross Section of Containment Cylindrical Wall and Induced Radial Compression

Considering Figure 5, it can be inferred that the horizontal tendons, with the convex shape, induce radial compression towards the centre of the radius of bend. The innermost concrete therefore is in compression due to both the inner and outer tendons' radially induced compression, while the concrete between the inner and outer tendons only experience compression from the outer tendons. The concrete outside the outer tendon (towards the external façade) does not experience direct compression from the horizontal tensioning. The same conclusion can be made for the tendons on the dome, i.e., convex tendons that are tensioned induce compression towards the radius of bend's centre, and therefore the concrete on the outside of the convex tendons does not experience direct compression from the tensioning.

It is therefore deduced that there is little effect on the tensioning and/or the compression stress in the concrete inside the tendon circumference if the concrete is removed on the outside of the tendons when considering convex tendons. Based on this, the dome and horizontal tendons are not analysed in this study.

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For the vertical, cylindrical section of the containments, the force in the tendons is distributed evenly throughout the concrete wall. This is illustrated graphically below, as seen in the ANSYS analysis (Figure 6). (Note the contour distribution that illustrates the distribution of the compression stress and the location of the cable). Negative values represent compression.

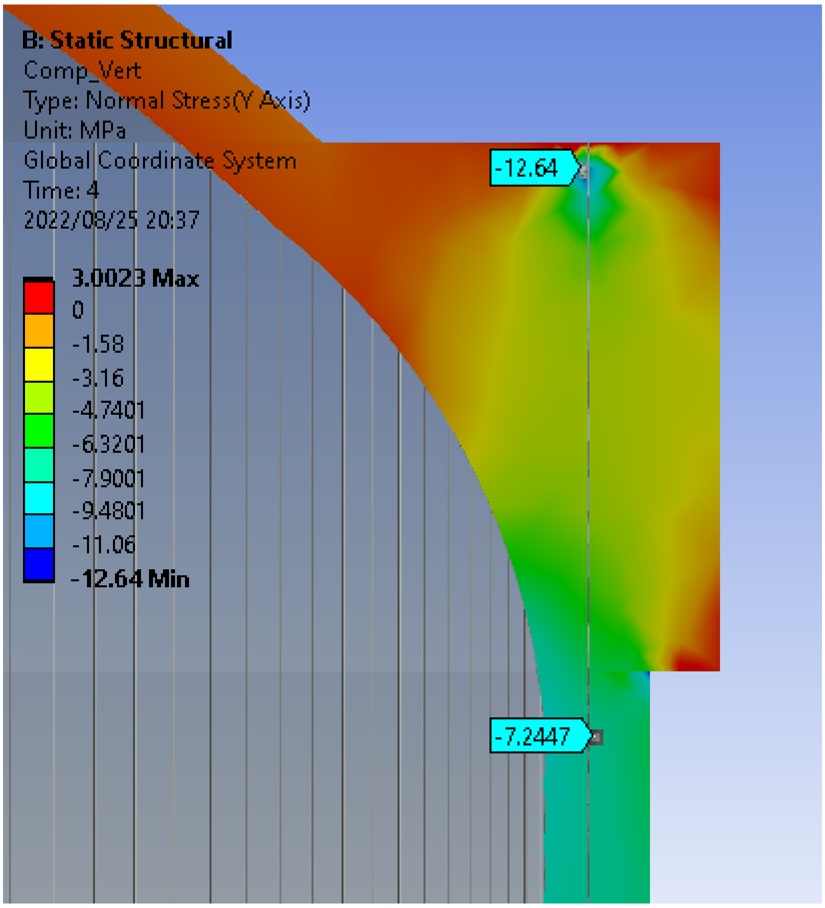

Figure 6: Compression stress distribution through vertical section due to vertical tensioning

The stress distributes evenly through the wall thickness due to the vertical tensioning and therefore the delamination of the external concrete mainly affects the vertical compression stress in the concrete. The vertical tensioning is therefore considered to determine the effect of delamination on the structure.

NOTE: The concrete compression stress is significantly lower than the compressive strength of the concrete and therefore concrete crushing is not a risk (7 MPa stress vs. +40 MPa strength).

4.3 FEA Results

For the first step, i.e., the initial tension, a uniform compression stress through the thickness of the containment is induced by the tension forces of the tendons (see Figure 7) with an average value of **8.6 MPa.**

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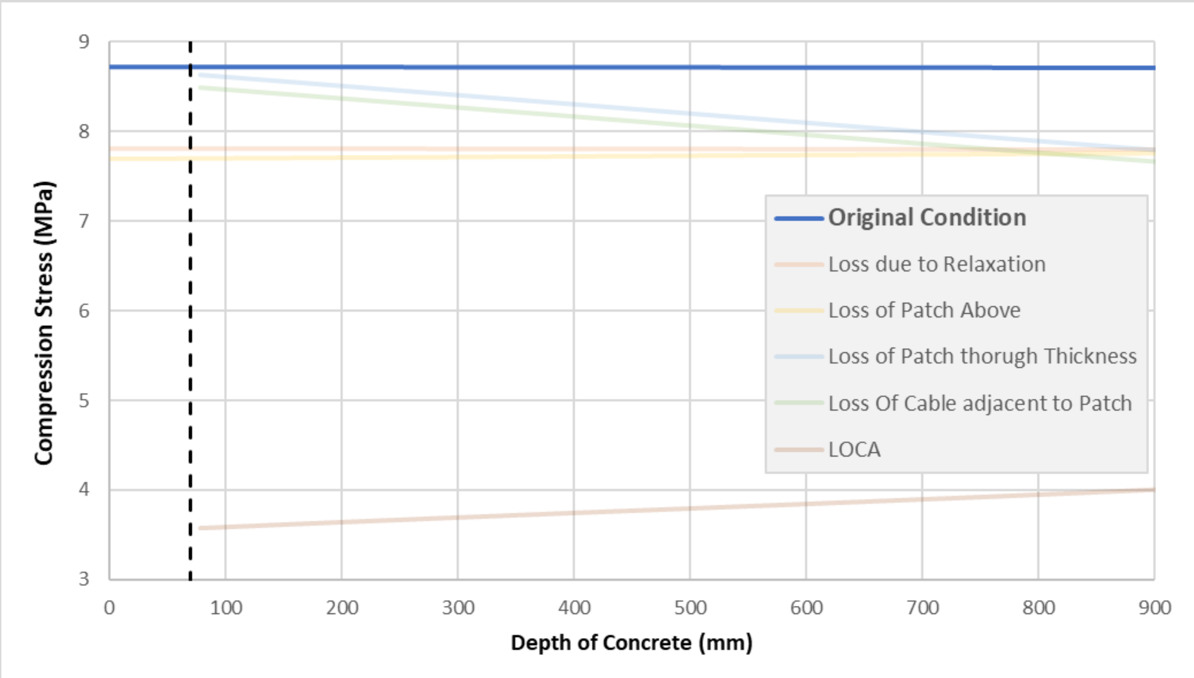

Figure 7: Compression stress through wall thickness after initial tensioning

Tensioning however relaxes due to several reasons over time. This relaxation was modelled as Step 2, and the effect on the compression stress monitored. The result, Figure 8, shows a uniform compression of **7.69 MPa**. The relaxation reduces the compression in the concrete therefore by roughly **1.1 MPa** or **10.182%.**

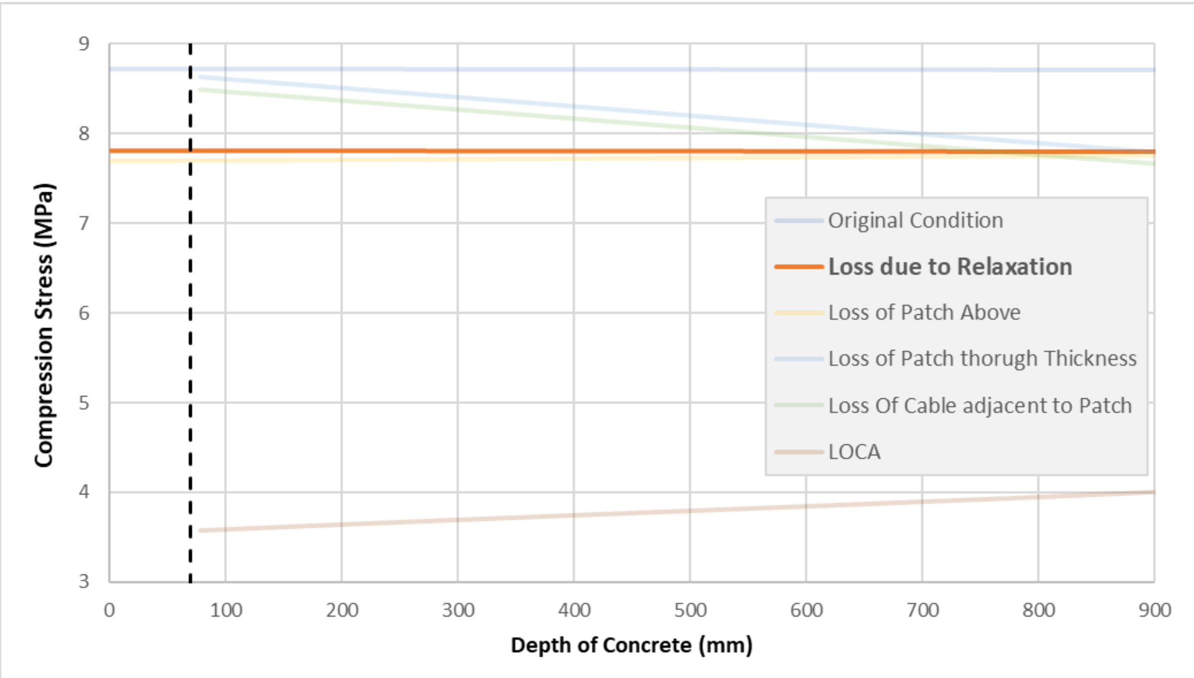

Figure 8: Compression stress through wall thickness after tensioning loss

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In Step 3, a large section of concrete loss is modelled, representing delamination of roughly 90 m² (Patch 2 in Figure 3). The delamination occurs above the area where the concrete stress is being determined. The effect is a slight reduction in uniform concrete stress from 7.69 MPa to **7.65 MPa**, or a **0.508%** change. The result is illustrated in Figure 9.

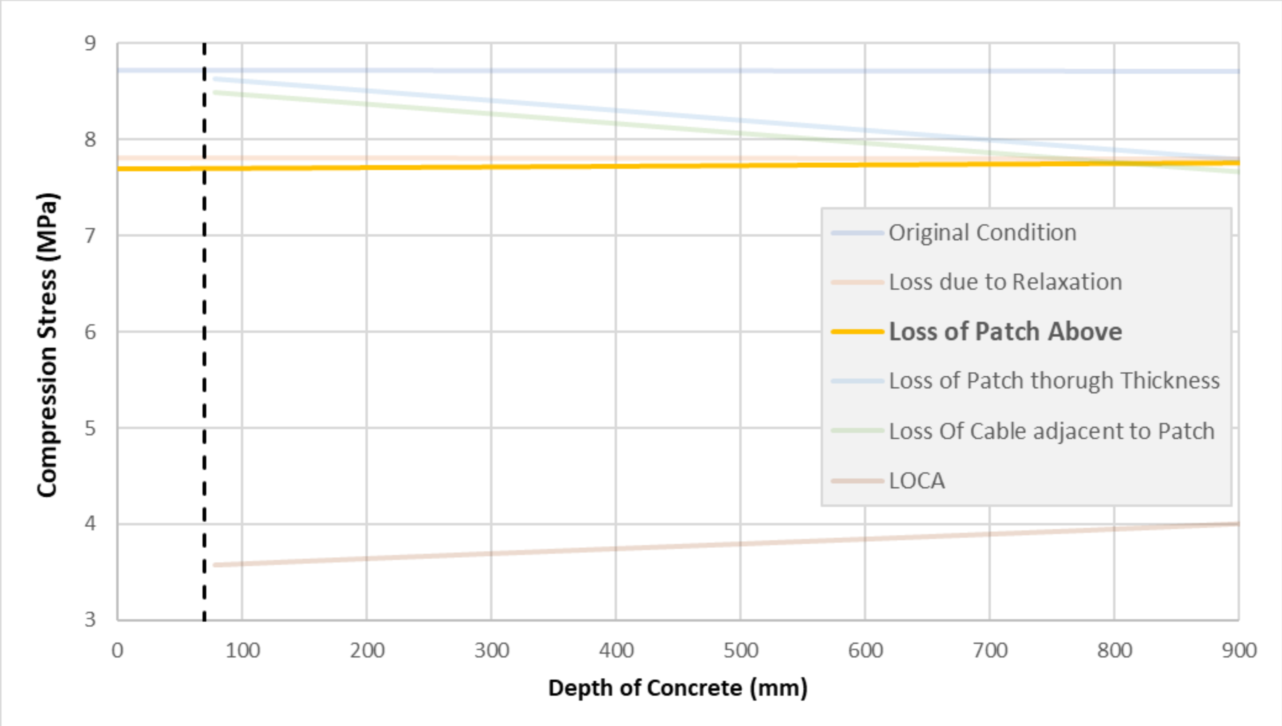

Figure 9: Compression stress through wall thickness after delamination <u>above</u> area being considered

The next Step analysed is a loss of cross section of 70mm in the area being investigated (Patch 1-B, Figure 3). The result has two aspects:

Firstly, the compression that originally existed in the area that has now delaminated, has to redistribute through the remainder of the concrete section. Secondly the stress distribution is no longer uniform throughout the section and is slightly askew, due to the redistribution. At the external face (where the delamination-intact concrete face exists) the concrete stress increased to 8.63 MPa and on the inner face the stress increased to 7.75 MPa. The non-uniformity is therefore not significant.

On average, the stress increased to **8.12 MPa** or **6.143 %**. The final result is highlighted in Figure 10.

Note that the increase in concrete compression stress is still lower than the original compressive stress induced by the tensioning of the tendons during construction.

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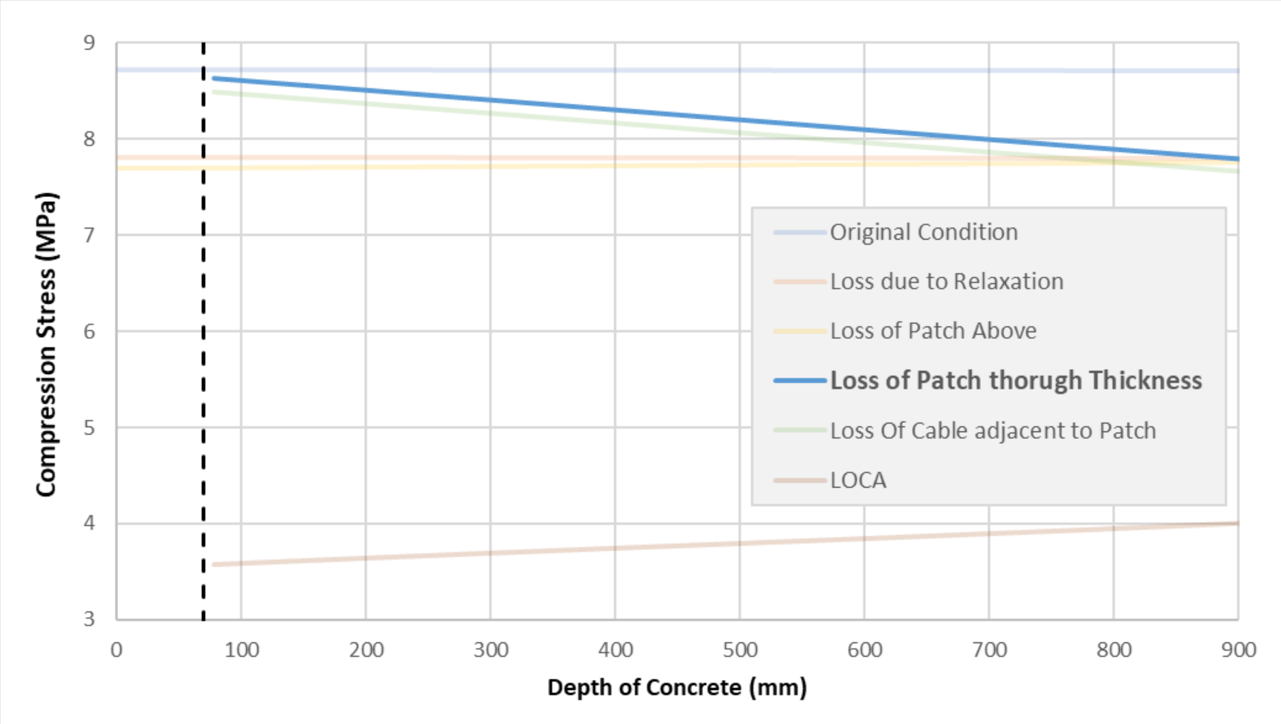

Figure 10: Compression stress through wall thickness after delamination through area being considered.

4.4 LOCA Conditions

In addition to the steps and results presented above, a complete cable break and a LOCA were also analysed. The effect of a LOCA had the greatest impact on the compressive stress in the concrete, with the average stress in the concrete (though a section that has experience delamination) being **3.89 MPa**, or a **49.43 %** loss in compression in the concrete section. The result indicates that the concrete still remains in compression with margin as dictated by the design rules of the containment structure during a LOCA. This result is similar to the finding of TLAA 301 and validates their findings, as discussed below.

The results of Step 1, Step 2 and Step 6 (Initial Load, Loss of Prestress and a LOCA) were compared to the results from TLAA 301 as indicated in Table 1. The ANSYS analysis yielded higher values of compression, however the error was relatively consistent.

The ANSYS results were conservatively adjusted downward to test the behaviour and result of the different methods of analysis and for comparison to the TLAA results. It is common that different analysis methods will yield different results, however the results can be validated by considering the behaviour or trends in the results and by considering if the results are in an acceptable range when compared to another.

The result is shown in Figure 11.

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It is shown that the different methods provided similar results and the behaviour of the analyses is very similar. The difference in results can be attributed to a number of different elements, however for the intention of the analysis, the result indicates the ANSYS model is validated and the finding of the TLAA is supported, i.e. that during a LOCA, even with the relaxation of the tendon, the structural integrity is assured for LTO by considering the design rule that the concrete needs to remain in compression.

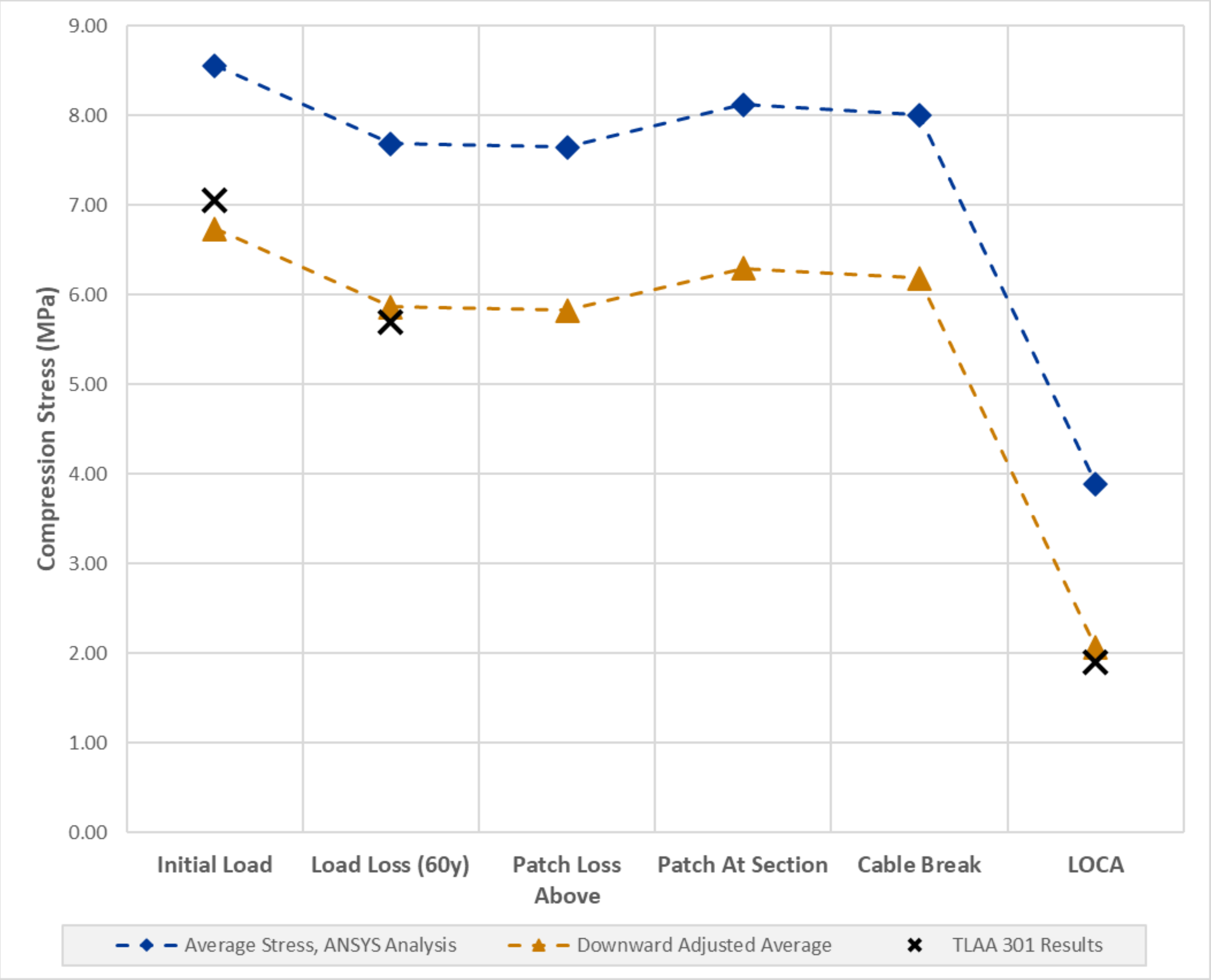

Figure 11: Average Compression through wall thickness for different scenarios and comparison to TLAA 301 results

The result of the ANSYS model however better considers the effect of the delamination and provides an in-depth view of the behaviour of the containment structure when subjected to delamination.

The TLAA delamination limit of 25 m^2 f is therefore increased based on the findings of this study.

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4.5 Loss of a Tensioning Cable

The ANSYS model was used to do a preliminary investigation into the consequences of the effects on the concrete compression stress due to the complete loss of a vertical cable. The cable used to replicate the complete loss of tension and its proximity to the patch used for investigation in § 4.2 above is illustrated below in Figure 13. The result is illustrated in Figure 11 for the average stress through the thickness and Figure 12 for the stress distribution through the thickness. The compression at the location being monitored reduced from an average of **8.12 MPa to 8.0 MPa**, or a reduction of **1.361 %.** The preliminary analysis indicates that the complete loss of a cable may not be detrimental to the integrity of the containment structures.

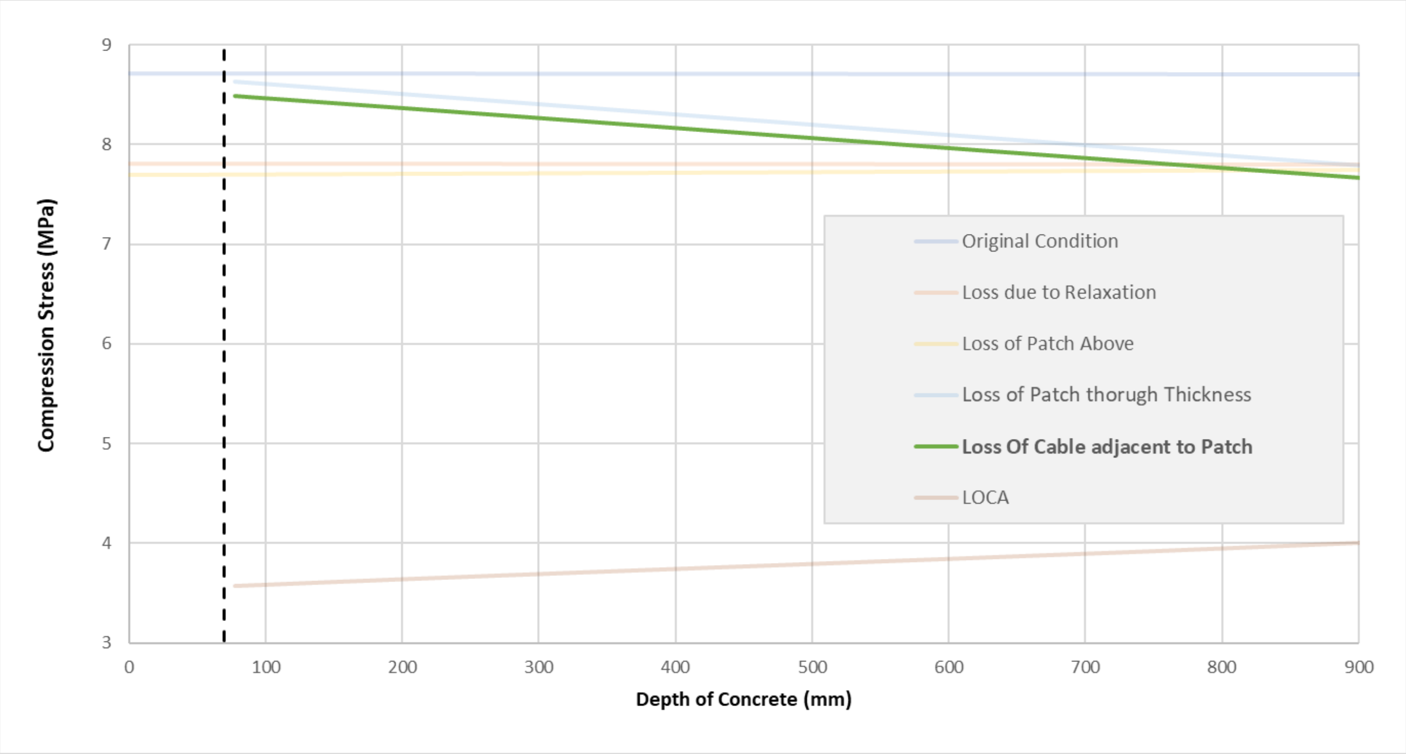

Figure 12: Compression stress through wall thickness after complete loss of a tendon, 1 m from area being considered

The current position is that there is a minor risk of currently having corroding tendons in the containment structure, and therefore the above analysis is not expanded into a comprehensive study into the loss of tendons.

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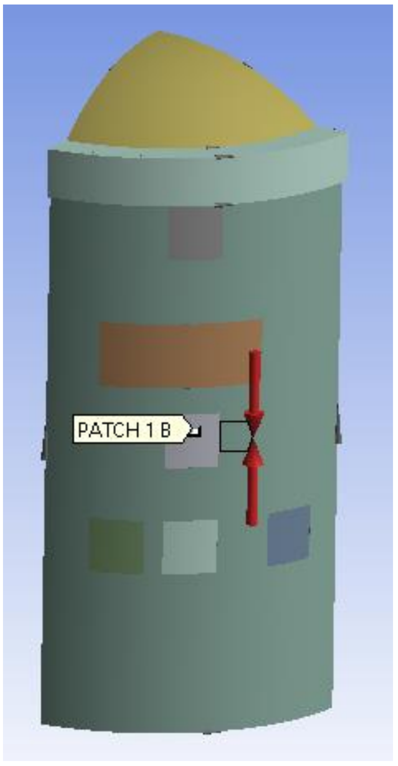

Figure 13: Location of modelled snapped cable

4.6 Ansys Software

ANSYS develops and markets engineering simulation software for use across the product life cycle. ANSYS Mechanical finite element analysis software is used to simulate computer models of structures, electronics, or machine components for analysing the strength, toughness, elasticity, temperature distribution, electromagnetism, fluid flow, and other attributes.

The ANSYS, Inc. quality system meets the requirements of ISO 9001:2008 [3], the internationally accepted quality standard administered by the International Organization for Standardization headquartered in Geneva, Switzerland. The ANSYS quality system also meets the United States Nuclear Regulatory Commission (NRC) rules and regulations for quality assurance 10CFR50, Appendix B, and the American Society of Mechanical Engineers (ASME) NQA-1 consensus quality standard, both of which set forth some of the most stringent software quality rules and requirements for the development of safety-critical software. In addition, ANSYS has worked with nuclear industry clients for years to provide QA services to satisfy quality assurance regulations for the structural analysis of nuclear equipment, thus enhancing the reliability of engineering simulation software and minimizing internal quality program maintenance costs.

ANSYS is the Eskom approved software for the finite element analysis and simulations.

ANSYS software has gone through verification and validation and has been approved for use by the Regulator in previous safety related modifications at Koeberg (Steam Generator Replacement, Reactor Vessel Head Replacement, Refuelling Storage Water Tank Replacement, etc.)

ANSYS t complies with the NNR regulatory guide RG-0016 [13].

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5 Conclusions

5.1 Structural Integrity Conclusion

5.1.1 The TLAA concluded that the structural integrity of the containment structures is verified for LTO as long as the tendons do not corrode. This report validates that analysis and goes one step further to note that, from a preliminary investigation conducted, the complete loss of a tendon will not be detrimental to the structural integrity of the containment.

5.1.2 The design intent of the ICCP modification is to minimise the risk that the chloride induced corrosion affects the tendons during LTO.

5.1.3 ICCP is not a requirement for LTO however the Expert Panel concluded that the only way to prevent corrosion on the tendons is through ICCP and therefore Eskom committed to install ICCP.

5.1.4 A preliminary FEM analysis indicated that the loss of a single tendon is not detrimental to the structural integrity of containment during LOCA conditions.

5.1.5 The continuous inspection and monitoring of the structures will detect any changes in the condition of the structures. Therefore, the status of the on-line monitoring equipment forms a crucial part of the continuous operation of the containment structures.

5.1.6 The TLAA limited the allowable delamination to 25m², however this study indicated that this limit is very conservative, and even at 215m² of delamination or replaced concrete on a quarter of the structure, there is limited negative consequences with respect to the compression design rule. There however remains a need to quantify the limit of allowable delamination on the structure before intervention is required (no spalling has occurred). The limit is therefore set to 100m² and is presented as an acceptable practical level by the Responsible Engineer. This will allow for economical repair projects, without jeopardizing the structural integrity of the containment structures and minimizing the invasive work on the structures.

5.1.7 It is however noted that there exists other implications when considering spalling such as the reduction in wall thickness, exposure of the reinforcement and a reduced cover to the tendons. The TLAA recommended that spalled areas be repaired immediately. Eskom will therefore consider the current repair specifications and determine an effective and practical repair methodology which can be implemented as soon as spalling is identified.

It is reiterated that the containment integrity is verified for LTO based on the TLAA and the analysis conducted in this report.

5.2 On-Line Monitoring

There are several issues with the on-line monitoring equipment. The on-line monitoring remains a crucial aspect of ensuring the behaviour of the structures are as expected in the periods between ILRT tests for the planned LTO period.

The TLAA recommendations on the on-line monitoring are therefore supported and these need to be completed as soon as possible.

Eskom compiled letter CE-18279 [4] to drive the issue and to present a holistic view of the status of the on-line monitoring equipment.

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5.3 Repair and Maintenance

The current inspection regime is deemed adequate.

It is however noted that the condition of the tendons is crucial to the structural integrity argument for the containment structures. It is therefore recommended that possible additional investigations and/or inspections be considered for the tendons which shall include the tendon heads.

5.4 ILRT

It is concluded that the ILRT may be performed during X27. Considering the status of the on-line monitoring equipment, it might even be beneficial to move the ILRT to X27 to provide Eskom the opportunity to implement the recommend improvements on the on-line monitoring which will aid the ILRT testing.

5.5 ICCP

The function of the ICCP modification is to ensure that the chloride induced corrosion does not reach the tendons and affect their ability to function as required by the design of the containment structure.

The TLAA did not link the safe LTO of the structures to ICCP and assumed no corrosion has occurred on the tendons.

It is concluded that ICCP is not an LTO requirement, and the structural integrity of the containment structures remain valid as long as the tendons do not corrode. Preliminary indications do however illustrate that the structures can resist the complete loss of a single tendon. As the current position is that the tendons have not corroded, this study falls short of conducting a full analysis into the loss of tendons and the preliminary investigation is only seen as indicative.

6 Acceptance

This document has been seen and accepted by:

Name	Designation
Sadika Touffie	Nuclear Engineering Manager
Ravid Goldstein	Design Engineering Manager
Anton Kotze	ETTM Chairperson (Acting)
Sasha Govender	Civil Engineering Manager

7 Revisions

Date	Rev.	Compiler	Remarks
September 2022	1	SJ Venter	First Compilation

8 Development Team

- Mr. Christopher Stolle, Pr. Tech. Eng., Chief Technologist
- Mr. Phumudzo Raliwedzha, Civil Engineer

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9 Acknowledgements

None