Selection Matrix for Non-Destructive Testing of NPP Concrete Structures

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Abstract. In general, the deterioration factors affecting concrete structures may be divided into (i) physical, (ii) chemical, and (iii) mechanical factors including also (iv) defects. Deterioration can result in loss of strength and unsafe conditions of the structures. NPP contain a variety of concrete structures that their structural performance of which is essential to the safety of the plant. Early detection of concrete structural deterioration in NPP is critical issue considering the consequence that they can eventually lead to. To ensure the safety and integrity of NPP, non-destructive testing (NDT) is carried out during the in-service life time. However, current NDT faces several challenges: (i) the NDT can be performed only during the revision time and the test process is time limited, (ii) the accuracy of the test devices, (iii) the compatibility of different NDT methods to the concrete structures and their deterioration mechanisms, (iv) the global uniformity of the NDT test methods and (v) the creditability of the test results and analysis.

This paper is critically assess the NDT techniques currently in use to build a selection matrix for non-destructive testing of NPP concrete structures ~~and to fulfil~~ for the needs of NPP infrastructure evaluation in Finland.

The results will specify the means for the assessment of suitability of different NDT methods for the NPP concrete structures. The results will also provide the nuclear power companies and utilities with reliable non-destructive test techniques to ensure the safety of the nuclear power plant facilities.

1 Introduction

Evaluation of existing NPP concrete structures is required as a result of identified degradation or abnormal performance, in support of physical modifications, or for periodical validation of structural integrity. Comprehensive evaluation of the NPP concrete structures at periodic intervals is also desirable to observe operational effects and possible degradation due to environmental conditions. This paper describes the development of a NDT selection matrix and the procedural steps that can be used to effectively select a suitable NDT technique via prioritized evaluation of the condition of NPP concrete structures [1]. The ultimate goal of the NDT selection matrix is to identify and describe the effective use of NDT technologies that can detect and characterize deterioration in NPP concrete structures. The selection matrix include representations of (i) the building materials used, (ii) the defects affecting the NPP concrete structures, and (iii) the inspection schedule for concrete structures. Fig. 1 presents a view of the NDT selection matrix and its criteria. The work is part of the project named NDE on NPP primary circuit components and concrete infrastructure (WANDA)[2], which is funded by the Finnish National Research programme on Nuclear Power Plant Safety SAFIR2018 [3].

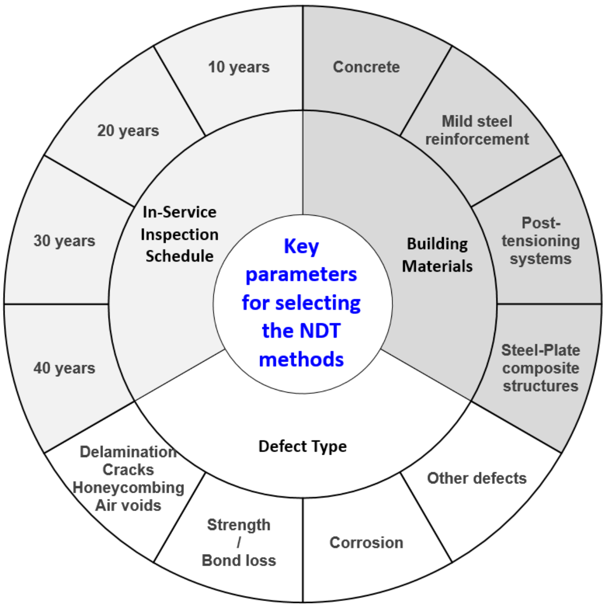

Fig. 1. A schematic description of the NDT selection matrix**.**

2 Classification of NPP Reinforced Concrete Structures

2.1 Safety Classification of Structures

In the Finnish regulatory framework, the systems, structures and components of the NPP are grouped into Safety Classes 1 (highest safety significance), 2, 3, and Class EYT (classified non-nuclear):

1. Safety class 1 (SC1) comprises of reactor fuel and major piping components and related structures in the reactor primary circuit boundary. There are e.g. no electrical or I&C systems or components in this class.
2. Safety class 2 (SC2) comprises of the critical safety systems that perform the necessary safety functions for maintaining reactor safety in disturbances and design based accidents. The safety functions are reactor shutdown, core cooling, residual heat removal and containment isolation.
3. Safety class 3 (SC3) includes systems having an essential effect on the reliability of the safety functions. Systems by which the accomplishment of the safety functions is monitored shall also be classified in SC3. In addition, SC3 shall include systems whose function is to reliably prevent the progression of initiating events into situations during which a system maintaining or actuating a safety function is needed.
4. Safety class 4 (SC4) is a new class introduced to systems that do not belong to a higher safety class and whose failure could, however, cause an initiating event that could significantly endanger nuclear or radiation safety. SC4 shall include systems that during internal or external initiating events protect systems carrying out safety functions, for example the fire and flooding protection systems. [4].

2.2 Classification of Materials and Products Used in Concrete Structures

The structural information of the NPP concrete structures is divided into structural parts for the development of the NDT selection matrix. The purpose for identifying structural parts is to (i) divide concrete structures into homogenous areas for analysis and (ii) provide the suitable NDT methods for each area.

The principle is that structural parts belonging to the same structure can be inspected and analysed without being divided into smaller parts. For instance several columns, beams, slabs or walls can be treated in the same module if they are materially and structurally similar and surrounded by same environmental conditions. On the other hand, a column or a wall which is exposed to different environmental conditions, e.g. water and air, cannot be treated as a single structural part and should be divided into two parts accordingly. An example of the classification of structural data and the used building materials is shown in Table 1. [5]

Table 1. Concrete structures related to the steel containment.

Structure name	Structural part	Building Materials		
		Reinforced concrete	Pre-stressed concrete	Steel-concrete composite structures
Auxiliary cooling system channels	Structures under water level	●		
Concrete structures inside steel containment	Concrete structures inside steel containment, crane wall	●		
	Internal cylinder of the reactor hole	●		
	Pool structures	●		
	Surrounding of the reactor coolant valve	●		
Containment	Foundation	●		
	Inner cylinder wall	●		
	Pre-stressed outer cylinder		●	
	Pre-stressed pool structures		●	
	Roof, under the steel liner			●
Cooling water intake plant	Basket filter area	●		
	Fine grating area	●		
	Sea water pump area	●		
Intake chamber to condenser	Structures under water level	●		
Outer shell	Cylinder (concrete) wall covered by corrugated steel sheet			●
	Part of the cylinder wall without cladding	●		
	Structures under water level	●		
Pump sumps	Pump sumps structures	●		
Structures exposed to sea water	Channels, inlet	●		
	Foundation of the containment	●		
	Inlet chambers of pumps	●		
	Main level floor slab, bottom surface	●		
	Pump rooms, dry area	●		

3 Classification of Defect Types of Concrete Structures

The exposure to the environment (e.g., temperature, moisture, cyclic loadings, etc.) can produce degradation of reinforced concrete structures. The rate of deterioration is dependent on the component's structural design, building materials selection, quality of construction, curing, and aggressiveness of environmental exposure, structural loading conditions. Primary mechanisms (factors) that, under unfavourable environmental conditions can produce premature deterioration of reinforced concrete structures include those that impact either the concrete or steel reinforcing materials (i.e., mild steel reinforcement or post-tensioning systems).

3.1.1 Concrete Defects

The degradation of the concrete can be caused by adverse performance of either its cement-paste matrix or aggregate materials under chemical or physical attack, and due to deficient workmanship during casting. The common types of defects in concrete structures include delamination/spalling, cracks and voids/honeycombing. Existence of such flaws in concrete severely affects durability, and therefore the service life, and in some cases can lead to the compromise of the structural integrity of concrete structures.

Delamination is a serious problem affecting the service life of reinforced concrete structures. The delamination is usually due to corrosion. The corrosion-induced delamination is horizontal cracked planes in concrete slabs. Delamination cracking generally occurs in a top steel layer, which is typically 5 cm to 15 cm below the concrete surface. The delamination will eventually propagate to the surface, causing large area spalling.

Cracks can be caused by drying shrinkage, thermal expansion, freeze-thaw cycling, chemical reaction and mechanical actions, such as fatigue or overloading. A distinct single surface-crack is a common and significant defect that can eventually lead to failure of concrete structures. Determining the width and depth of cracks is essential to integrity assessment of concrete structures.

Voids and honeycombing are usually caused by poor consolidation of concrete during construction. Voids due to incomplete grouting in post-tension ducts leave tendons vulnerable to corrosion, and can eventually lead to failure of the structure.

3.1.2 Mild Steel Reinforcing Defect

Degradation of mild steel reinforcing materials can occur as a result of corrosion, irradiation, elevated temperature, or fatigue effects, with corrosion being the most likely form of attack [6]. The basic problem associated with the deterioration of reinforced concrete is corrosion products, i.e. rust. The formation of rust involves a substantial volume increase (a factor of about 2 - 7) which causes cracking, spalling and staining of concrete, and reduces the effective cross-sectional area of reinforcing bars and weakens the bond between reinforcement and concrete, seriously affecting the durability, and the service-life of structures [7].

3.1.3 Defects of Prestressed Systems

Post-tensioning systems are susceptible to the same degradation mechanisms as mild steel reinforcement plus loss of pre-stressing force, primarily due to tendon relaxation, and concrete creep and shrinkage. Many of the problems associated with post-tensioned systems can be attributed to grouting which is used to protect corrosion of steel strands inside the duct. In post-tensioned systems the ducts of plastic or metal are either imbedded in concrete or they can be installed externally. The major problems with ducts are: cracked polyethylene (PE) ducts; grout voids; problematic grout (unset, wet, soft, contaminated and chalky); strand corrosion and tendon failure.

3.1.4 Steel-Concrete Composite Structures Defects

Defects can inadvertently be produced in composite materials, either during the manufacturing process or in the course of the service life of the component. The manufacturing process has the potential for causing a wide range of defects, the most common of which is "porosity," the presence of small voids in the matrix. Porosity levels can be critical, as they will affect mechanical performance parameters, such as internal laminar shear stress. Composite structures with honeycomb can suffer from poor bonding of the skin to the core. Just like any steel structure, the faceplates steel surfaces is affected by corrosion [8].

3.1.5 Summary of Concrete Structures Defects

Table 2 summarizes primary mechanisms (factors) which can produce premature deterioration of reinforced and post-tensioned concrete structures.

Table 2. Degradation factors that can impact the NPP concrete structures and their consequences [9].

Material System	Degradation Factor	Primary defects												
		Corrosion	Cracking	Spalling	Scaling	Volume change/ Section loss	Disintegration/ material loss	Volume change	Bond loss	Strength loss	Ductility loss	Misalignment	Increased porosity	Leaching
Concrete	Physical processes													
	Salt crystallization		●				●							
	Freezing and thawing		●		●		●							
	Abrasion/erosion/cavitation					●								
	Thermal exposure/thermal cycling		●	●						●				
	Irradiation		●					●						
	Fatigue/vibration		●											
	Settlement		●	●								●		
	Chemical processes													
	Efflorescence/leaching												●	
	Sulfate attack		●					●						
	Delayed ettringite formation		●					●						
	Acids/bases			●			●							●
	Alkali-aggregate reactions		●				●							
	Aggressive water						●							
	Biological attack					●							●	
Mild steel reinforcement	Corrosion	●	●	●		●								
	Elevated temperature									●				
	Irradiation										●			
	Fatigue								●					
Post-tensioning system	Corrosion	●								●	●			
	Elevated temperature									●				
	Irradiation													
	Fatigue		●											
	Stress relaxation/end effects									●				
Liner/structural steel	Corrosion	●				●								
	Elevated temperature									●				
	Irradiation										●			
	Fatigue		●											

4 Selection Matrix for Non-destructive Testing Techniques

The NDT techniques can be used to ensure the quality right from raw material stage through fabrication and processing to pre-service and in-service inspection. Apart from ensuring the structural integrity, quality and reliability of components and plants, the NDT finds extensive applications for condition monitoring, residual life assessment, energy audit, etc. There are many NDT techniques/methods used, depending on four main criteria: (i) material type, (ii) defect type, (iii) defect size and (iv) defect location [10].

4.1 Estimation of the Deterioration Phases for Concrete Structures

Usually researchers considered corrosion initiation and propagation as two significant phases of service life. However, it has been observed that service life of a structure has three major phases – (1) period after construction and before corrosion initiation (2) the period between corrosion initiation and crack formation (3) the period after crack formation before failure of structure as shown in Figure 2 [11] & [12].

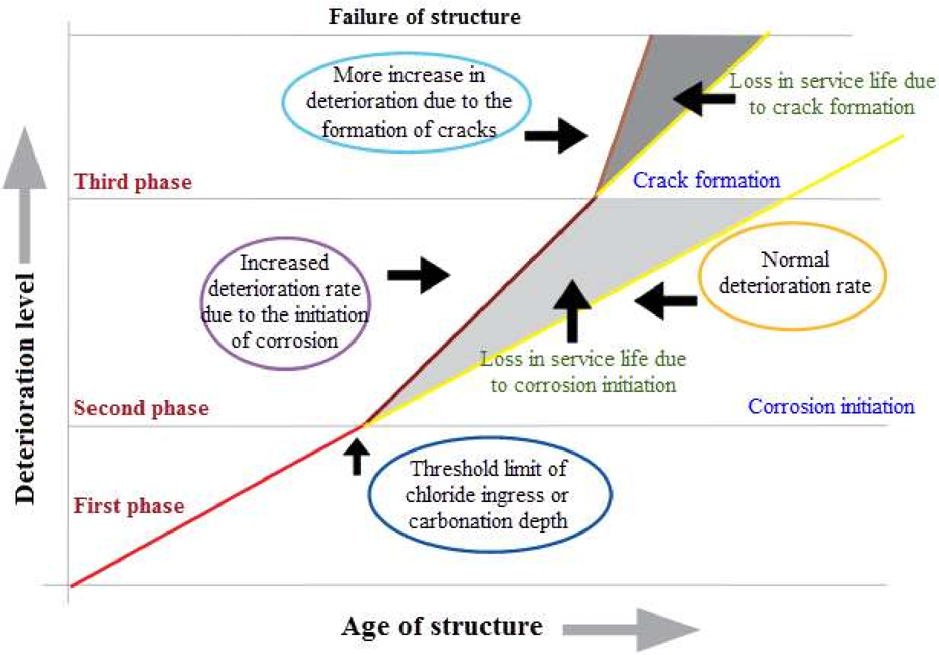

Fig. 2. Main events related to the service life of concrete structures [11].

Based on the events related to the service life of concrete structures presented in Fig. 2, the selection of NDT methods can be divided into the following categories:

1. First phase NDT methods: The NDT methods are selected to monitor the actual conditions both regarding execution details such as homogeneity and quality, which over time may ensure that the structure fulfils its required function and design life. If defects or lack of quality are observed during the construction phase, these can be corrected to avoid expensive repair costs at a later stage. Examples of the first phase NDT methods are the detection of honeycombs, measuring the carbonation depth, the chloride content, concrete cover, and concrete quality measurements.
2. Second phase NDT methods: NDT methods for the structural conditions during the operations phase. Visual inspections only reveal what is visible at the surface, while NDT methods can inspect the concrete structures condition and as such give information about hidden detrimental features such as cavities and air voids. The NDT methods during the initiation phase of deterioration are used to examine the concrete cover around reinforcement, that can be deteriorated by the surrounding environment, because of various origins: (i) physical causes: freezing, etc; (ii) mechanical causes: concrete can crack under an excessive loading, and (iii) chemical causes, for example, due to bodies (gas or ions) contained in the environment.
3. Third phase NDT methods: NDT methods during the propagation phase (de-passivation to the spalling phase), which can assess the concrete structures cracking, delamination, corrosion and reinforcement placing.

4.2 Classification of Non-Destructive Testing Techniques

In Table 3 a summary of potential damage types and suitable non-destructive testing techniques for assessing them is given. The testing methods listed represent state-of-the-art techniques for in-situ testing of concrete. The summary evaluation of the methods in terms of reliability and usefulness is based on practical experience in specific situations and it is not intended that these evaluations be universally applied to the given techniques [13].

Table 3. Non-destructive Testing of Concrete structures - Testing Methods & Damage type [13].

NDT method	Abbr.	Material	Application	Reliability	Usefulness
Acoustic Emission	AE	Concrete	Continuous monitoring of structure during service life	unknown	unknown
Carbonation Depth Test	CARB	Concrete	Carbonation depth of concrete	Good	Good
Concrete Cover Meter Testing	COV	Steel	Location of reinforcement / Size of reinforcement	Fair	Poor
Electrical Resistivity	ER	Steel / Concrete	Concrete resistivity (related to corrosion rate)	unknown	Good
Galvanostatic Pulse Method	GPM	Steel	Detection of actively corroding reinforcement (electrochemical)	Good	Good
Ground penetrating radar	GPR	Steel	Location and size of reinforcement / Location of pre-stressed cable ducts	Fair	Fair
Half-cell electrical potential method	HCP	Steel	Detection of actively corroding reinforcement (electrochemical)	Good or Fair	Good
Impact Echo	IE	Concrete	Cracking internally / Thickness of concrete member or layer	Good	Good
Impulse Response	IR	Concrete	Delamination and honeycombs / Voids in concrete and homogeneity	Fair	Poor
Infrared Thermography	IRT	Concrete	Delamination and honeycombs	unknown	unknown
Linear Polarization Resistance	LPR	Steel	Estimation of reinforcement corrosion rate (electrochemical)	Fair	Fair
MIRA - Ultrasonic Pulse Echo Imaging	MIRA	Concrete	Voids in concrete and homogeneity / Delamination and honeycombs / Detection of voids in pre-stressed cable ducts	unknown	unknown
Radiographic testing	RAD	Steel	Location and size of reinforcement / Grouting condition in the post-tensioning ducts	Fair	Fair
Schmidt Rebound Hammer	SRH	Concrete	Damaged concrete layers (reduced strength and elastic properties)	Fair	Fair
Spectral Analysis of Surface Waves	SASW	Concrete	Reduced strength and elastic properties / Thickness of concrete member or layer	Good	Good
Ultrasonic Pulse Echo	UPE	Steel	Detection of voids in pre-stressed cable ducts	Fair	Fair or Poor
		Concrete	Cracking in surface and internally	Good or Fair	Fair
Ultrasonic Pulse Velocity	UPV	Concrete	Cracking / reduced strength	Fair	Fair
Windsor Probe Testing	WPT	Concrete	Compressive strength of in-place concrete	Fair	Fair

4.3 Selection Procedure of the NDT Methods

Non-destructive testing technology is generally divided into three categories:

1. To estimate in-situ strength of the materials.
2. To provide material properties such as moisture, density, elastic wave velocity, elastic constant, thickness and temperature.
3. To detect and locate objects and problem areas within structures such as cracks, honeycombing, delamination, rebar, flaws and deterioration.

NDT methods developed to-date are classified into four levels according to their performance:

- Level 1 that only identifies if damage has occurred.
- Level 2 that identify the occurrence of damage and its location.
- Level 3 that identify the occurrence of damage and its location and also estimate the severity of the damage.
- Level 4 that identify the occurrence of damage and its location, estimate its severity, and evaluate the impact of damage on structures.

With this in mind, a selection procedure of the suitable NDT methods for the reinforced concrete structures has been defined, and is demonstrated as follow:

1. The structure and structural part is selected, see Table 1.
2. Select the building material for the target structural part, see Table 1.
3. Select the expected defect of the structural part based on the building material and the age of the structure, see Table 2.
4. Select the suitable NDT method based on the information above.

Table 4. Example of the NDT methods' selection matrix for the NPP containment (Abbreviations of the NDT methods' names are shown in **Table 3**).

Structure	Structural part	Building Materials	Expected defects				Suitable NDT methods			
			0 - 10 years	10 - 20 years	20 - 30 years	30 - 50 years	0 - 10 years	10 - 20 years	20 - 30 years	30 - 50 years
Containment	Foundation	Concrete Material Systems	Air Voids	External cracks	Delamination	Reduced strength	UPV, UPE, SASW, IE, GPR	UPV, UPE, SASW	UPV, UPE, SASW, IE	SRH, UPV, SASW, GPR
			Layer Thickness	Internal cracks	Internal cracks		COV	UPV, UPE, SASW, IE	UPV, UPE, SASW, IE	
	Inner cylinder wall		Honeycombs	Carbonation depth	Carbonation depth		UPV, UPE, SASW, IE, GPR	CARB	CARB	
				Reduced strength	Reduced strength			SRH, UPV, SASW, GPR	SRH, UPV, SASW, GPR	
	Foundation	Mild Steel Reinforcing Systems	Bar location	Estimation of reinforcement corrosion rate	Corrosion	Corrosion	COV	HCP, ER, LPR, GPM, RAD	HCP, GPM, GPR	HCP, GPM, GPR
	Inner cylinder wall		Bar size	Concrete resistivity			COV	ER		
			Concrete Cover depth				COV			
	Pre-stressed outer cylinder	Post-Tensioning Systems	Location of pre-stressed cable ducts	Estimation of reinforcement corrosion rate	Corrosion	Corrosion	MIRA, RAD	HCP, ER, LPR, GPM, RAD	HCP, GPM, GPR	HCP, GPM, GPR
	Pre-stressed pool structures			Concrete resistivity				ER		
	Roof, under the steel liner	Steel-concrete composite	Honeycombs	Reduced strength	Corrosion	Corrosion	MIRA, RAD	SRH, UPV, SASW, GPR	HCP, GPM, GPR	HCP, GPM, GPR

The research presented in this paper provides background information the developing work with in the WANDA project. A testing program of the full-scale thick concrete wall will be set up for calibrating NDT methods, investigating the correlation between results received by different methods, studying the effect of time dependency and testing conditions on the results and their relative accuracy. The purpose of this full-scale concrete wall is to provide conditions for continuous long term testing (longer than 10/20 year) which makes it possible to assess the reliability of different tools and methods in a well-documented situation [2].

5 Conclusions

The early detection of concrete structural deterioration in NPP is critical issue considering the consequence that failure to fulfil performance criteria can eventually lead too. To ensure the safety and integrity of NPP, NDT is carried out during the operation. However, current NDT technologies faces several challenges: the NDT can be performed only during the revision time and the test process is time limited, the accuracy of the test devices, the compatibility of different NDT methods to the concrete structures and their deterioration mechanisms, the global uniformity of the NDT test methods and, the creditability of the test results and analysis. So as to address these difficulties, a methodology to assist NPP engineers in the choice of NDT method to be applied.

The aim of this paper is to describe a NDT selection matrix and the procedural steps that can be used to effectively select a suitable NDT technique via prioritized evaluation of the condition of NPP concrete structures. The objective of the NDT selection matrix is to identify and describe the effective use of NDT technologies that can detect and characterize deterioration in NPP reinforced concrete structures. The NDT selection matrix selection criteria takes into consideration the building materials used, the possible defects affecting the NPP reinforced concrete structures, and the inspection schedule for reinforced concrete structures. The NDT selection matrix is useful for an effective selection of the suitable NDT technique for NPP concrete structures based on their building materials and in-service age.

6 References

[1] Al-Neshawy, F., Ferreira, M., Bohner, E., (2016). NDE of thick-walled reinforced concrete structures – Selection matrix for non–destructive evaluation of NPP concrete structures. VTT Research Report. VTT-R-00215-16. 2016. 88p.

[2] Jäppinen, T., Ferreira, M., Al-Neshawy, F., (2015). WANDA - Non-destructive examination of NPP primary circuit components and concrete infrastructure. Project Plan 2015-2018. SAFIR 2018. 2015. 19p.

[3] Hämäläinen, J., & Suolanen, V. (2015). SAFIR2018 – The Finnish Research programme for Nuclear Power Plant Safety 2015-2018. Annual Plan 2015. VTT Research Report. VTT-R-02813-15. 2015.

[4] Holmberg, J-E., Männistö, I. (2008). Risk-informed classification of systems, structures and components. Rakenteiden Mekaniikka (Journal of Structural Mechanics). Vol. 41, No 2, 2008, pp. 90–98.

[5] YVL E.6 (2013). Buildings and structures of a nuclear facility. Guide YVL E.6, Radiation and Nuclear Safety Authority (STUK), Helsinki, November 2013. Retrieved from: http://www.finlex.fi/data/normit/41746-YVL_E.6e.pdf [Accessed on 17.02.2016]

[6] Naus, D.J., Braverman, J.I., Miller, C.A., Ellinwood, B.R., Hofmayer, C.H., (2000). Factors Related to Degradation on Nuclear Power Plant Concrete Structures. PRO 16: International RILEM Workshop on Life Prediction and Aging Management of Concrete Structures. Cannes, France, 16–17 October 2000.

[7] Abosrra, L. R., (2010). Corrosion of mild steel bars in concrete and its effect on steel-concrete bond strength.Ph.D. Thesis, School of Engineering, Design and Technology University of Bradford, UK. 2010.

[8] Smith, R.A. (2009). Composite Defects and Their Detection. Materials science and engineering – Vol. III, pp.103-143. Uunesco-Eolss, sample chapters. – Retrieved from: http://www.eolss.net/sample-chapters/c05/e6-36-04-03.pdf [Accessed on 18.02.2016]

[9] IAEA, (2016). Ageing Management of Concrete Structures in Nuclear Power Plants, International Atomic Energy Agency. IAEA - Nuclear Energy Series No. NP-T-3.5, Vienna, 2016.

[10] McCann, D.M., Forde M.C., (2001). Review of NDT methods in the assessment of concrete and masonry structures. NDT & E International, Volume 34, Issue 2, March 2001, Pages 71–84.

[11] Verma, S. K.; Bhadauria, S. S. and Akhtar, S., (2014). Computational methods in service life modeling of concrete structures. The Indian Concrete Journal March 2014. Retrieved from: https://www.icjonline.com/views/2014.03._PointOfView.pdf [Accessed on 18.02.2016].

[12] Verma, S. K.; Bhadauria, S. S.; and Akhtar, S., (2013). Review of Nondestructive Testing Methods for Condition Monitoring of Concrete Structures," Journal of Construction Engineering, vol. 2013, Article ID 834572, 11 pages, 2013. doi:10.1155/2013/834572

[13] Shaw, P., (1997) "Assessment of the Deterioration of Concrete in NPP – Causes, Effects and Investigative Methods". NDTnet 1998 February, Volume3 No. 2. Retrieved from: http://www.ndt.net/article/0298/shaw/shaw.htm. [Accessed 18.02.2016]