Deterministic and probabilistic structural integrity analysis of the reinforced concrete structures

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DETERMINISTIC AND PROBABILISTIC STRUCTURAL INTEGRITY ANALYSIS OF THE REINFORCED CONCRETE STRUCTURES

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PREFACE

The objective of this monograph is to summarise the scientific research in the structural integrity analysis field as applied to Nuclear Power Plant reinforced concrete structures. The described research areas were performed by the authors of this monograph during the years 1995-2006. The research presented in this monograph applies to structural integrity investigations of Ignalina NPP buildings due to static and dynamics loads.

The nuclear reactors of the Ignalina nuclear power plant (NPP) belong to the RBMK class of reactors, designed and constructed by the Ministry of Nuclear Power Construction of the former Soviet Union. These reactors do not possess the conventional Western containment structure that could confine the radioactive products of a severe nuclear accident. Instead, the Ignalina NPP has a suppression type containment, which for Soviet-built reactors is referred to as the accident localisation system (ALS). The ALS encloses about 65% of the entire cooling circuit and this includes the most dangerous sections of piping to rupture in case of the loss-of-coolant accident (LOCA).

The ALS reinforced concrete building for the RBMK-1500 reactors is comprised of two similar towers adjacent to the reactor unit. The ALS towers are interconnected through a system of the leak-tight compartments designed for steam discharge in case of rupture in the primary coolant circuit. The ALS is required to prevent the release of radioactive materials from reaching the atmosphere in case of the coolant piping rupture, including the Design Base Accident (DBA). The importance of the ALS analysis is the demonstration of the structural integrity of ALS in case of maximum design basis accident (MDBA) which refers to a guillotine rupture of the pressure header of the main circulation pumps.

Both deterministic and probabilistic methodologies were used for structural analysis of reinforced concrete structures. These structures are made from materials with very different material properties, i.e. concrete and steel. Therefore, for strength analysis, sophisticated methods that account for these differences must be used. The finite element method was applied for structural analysis of reinforced concrete structures. The deterministic structural integrity analysis considered loadings due to operation and accident conditions and was based on the accepted geometrical data and material properties of constructions. However, the loadings, geometrical data and material properties are uncertain. The estimation of the uncertainties of initial data to strength of structures is very important. Thus, probabilistic analysis methods are used for the evaluation of uncertainties. A probability-based structural integrity analysis was performed as the integration of deterministic and probabilistic methods using existing state-of-the-art software for Ignalina NPP buildings. The NEPTUNE and ProFES software were coupled for these analyses. Using the coupled software, the analysis of the dependence between loading, geometrical data, material properties parameters on the failure probability of reinforced concrete structures was obtained.

Many individual and several cooperative projects designed for structural integrity analysis of Ignalina NPP buildings, mainly ALS, were performed in the years 1995 - 2006. In this respect the following projects should be mentioned:

- Ignalina ALS Safety Case, Probabilistic Safety Analysis of Level 2;
- Simulation of Ignalina RBMK-1500 ALS Containment Capacity Using NEPTUNE;
- Evaluation of Pipe Whip Impacts on Neighbouring Piping and Walls of the Ignalina RBMK-1500 NPP;
- Strength Evaluation of Steam Distribution Header and their Connections to the Vertical Steam Corridors of the Ignalina NPP;
- Analyses of Ignalina RBMK Nuclear Power Plant Buildings and Structures for External Loading Conditions.

Some of these projects were carried out in cooperation with specialists from Argonne National Laboratory. The material presented in this monograph describes the main results of the mentioned projects.

The methodologies and results of linear and non-linear analysis of the reinforced concrete structures subjected to static and dynamic loads are presented in this monograph. Normal mechanical properties of concrete and reinforcement bars were used in the linear analysis. The concrete strength in compression was also considered and assumed to be equal to zero in tension. The results of the linear analysis are conservative. The experimental mechanical properties of the concrete and reinforcement bars were used for the non-linear analysis which also evaluated the concrete strength for tension and compression. The failures of concrete and reinforcement bars as well as the thickness of destroyed concrete were determined in the non-linear analysis.

The static structural integrity analysis of buildings was performed using internal pressure, concentrated and temperature loadings. The dynamic structural integrity analysis of buildings was performed using the loads from internal impact events onto the internal surface of walls and transient loads onto the external surface of walls from an aircraft crash. The non linear analyses under dynamic loads were performed using both deterministic and probabilistic structural integrity analyses. The following methods were used for numerical probabilistic analysis of reinforced concrete structures: Monte Carlo simulation, the First-Order-Reliability- method and Response Surface / Monte Carlo Simulation.

The deterministic and probabilistic methodologies for structural analysis of reinforced concrete structures are presented in this monograph. The applications of these methodologies were applied to Ignalina NPP buildings, as examples. However, these methodologies can be used not only for NPP buildings, but also for other reinforced concrete structures that have strict requirements for safety: for example, bridges, dams, chemical plants energy facilities, and pylons for electricity lines. In addition to reinforced concrete structures, these methodologies can be used for steel constructions where failure would create dangerous environment conditions: for example, heat, gas and oil pipeline systems, steel devices within chemical plants and energy industry.

The authors of this monograph would like to acknowledge Professor A. Marchertas, who is one of the initiators of structural integrity analysis of the Ignalina NPP ALS in the Lithuanian Energy Institute. Prof. A. Marchertas provided the first lessons in strength analysis of reinforced concrete structures using the finite element method.

The authors of this monograph would like to acknowledge the Pacific Northwest National Laboratory (USA), Argonne National Laboratory (USA) and Applied Research Associates Southeast Division (USA) for providing the NEPTUNE, TEMP-STRESS and ProFES code versions. The authors from LEI would like to acknowledge Dr. R. F. Kulak from “RFK Engineering Mechanics Consultants” (USA) for his technical consultation on using the above software packages. We also want to extend our thanks to the administration and technical staff of Ignalina NPP, for providing information regarding operational procedures and the operational data. The authors acknowledge the following scientists of Lithuanian Energy Institute: Mr. Renatas Karalevicius for contribution in preparing finite element models of Ignalina NPP reinforced concrete structures and Dr. Robertas Alzbutas for help in application of the probabilistic analysis methods for reliability analysis of reinforced concrete structures.

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CONTENT

NOMENCLATURE

a, b, c, d	–	Failure parameters
A	–	Area of pipe, m^2
A_{wall}	–	Cross-section area of the pipe wall, m^2
b_w	–	Cross-section width, m
d_p	–	Inner diameter of the pipe, m
D_p	–	Outer diameter of the pipe, m
D_{eng}	–	Equivalent diameter of the engine, m
D	–	Reference strain-rate, 1/s
E_{red}	–	Reduced modules of elasticity, MPa
E_c	–	Initial elasticity of the concrete, MPa
E_s		Initial elasticity of the steal, MPa
f_c	–	Uniaxial compressive strength of concrete, MPa
f_t	–	Uniaxial tensile strength of concrete, MPa
f_{bc}	–	Equal biaxial compressive strength of concrete, MPa
f_{pc}, f_{cc}	–	Combined triaxial compression of concrete, MPa
f_y		Yield strength of reinforcement, MPa
f_{dc}	–	Dynamic compressive strength, MPa
f_{cs}	–	Static compressive strength, MPa
f_{dt}	–	Dynamic tensile strength, MPa
f_{ts}	–	Static tensile strength, MPa
F_c	–	Load contribution from aircraft crushing strength, N
f_{iI}^{int}	–	Internal nodal forces of node I in the i-th direction, N
f_{iI}^{ext}	–	External nodal forces of node I in the i-th direction, N
h_o	–	Thickness of the wall, m
h	–	Thickness of the spacing of reinforcement layers in the respective directions, m
h_1	–	Thickness of the reinforcement layer, m
I	–	Moment of inertia, m^4
I_1, J_2	–	Stress invariants, MPa, $(MPa)^2$

l	–	Length of the straight pipe, m
m_{iI}	–	Diagonal mass matrix of node I in the i-th direction
M	–	Mass of the missile, kg
M_2	–	Bending moment with respect to axis 2, N-m
M_3	–	Bending moment with respect to axis 3, N-m
n	–	Step number
P	–	Axial force, N
p_k	–	Pressure at the break location, Pa
p_a	–	Outside (atmospheric) pressure, Pa
p_{wall}	–	Pressure straight after the break location, Pa
p	–	Reinforcement ratio
q	–	Steel strain-rate amplitude parameter
Q_x	–	Reaction force, N
S_2	–	Sectional modulus with respect to axis 2, m^3
S_3	–	Sectional modulus with respect to axis 3, m^3
t		Wall thickness, m
t_c	–	Thickness of reinforcement with prevailing compression, m
t_p	–	Minimum wall thickness to prevent perforation, m
t_{pd}	–	Minimum design thickness to prevent perforation, m
t_s	–	Minimum wall thickness to prevent scabbing, m
t_{sd}	–	Minimum design thickness to prevent scabbing, m
t_t	–	Thickness of reinforcement with prevailing tension, m
Δt	–	Time increment, s
U	–	Reference velocity, m/s
u_{iI}	–	Nodal displacement of node I in the i-th direction, m
$\dot{u}_{iI}$	–	Nodal velocity of node I in the i-th direction, m/s
$\ddot{u}_{iI}$	–	Nodal acceleration of node I in the i-th direction, m/s^2
v	–	Velocity of the uncrushed part of the plane relative to the wall, m/s
V	–	Velocity of the engine, m/s
w_k	–	Fluid velocity at the break location, m/s
x	–	Thickness of a concrete layer under compression in the corresponding part of the reinforcement, m.

Greek letters

α, α_{fy}, α_{fu}	–	Parameters
β, δ	–	Parameters
$\dot{\varepsilon}$	–	Strain-rate, 1/s
$\dot{\varepsilon}_s$	–	Static strain-rate, 1/s
μ	–	Mass per unit length, kg/m
ρ_k	–	Fluid density at the break location, kg/m^3
σ_a	–	Axial stress, MPa
$\sigma_{b2/3}$	–	Bending stress with respect to axis 2 and 3, MPa
σ_{dyn}	–	Dynamic flow stress, MPa
σ_1	–	Maximum principal stress, MPa
σ_y	–	Normal stress, MPa
σ_{static}	–	Static flow stress, MPa
σ_{worst}	–	Worst stress, MPa
τ_u	–	Transverse shear failure, MPa

Abbreviations

ALS	–	Accident Localisation System
BSRC	–	Bottom Steam Reception Chamber
BWR	–	Boiling Water Reactor
CFAIL	–	Concrete Failure
DIF	–	Dynamic Increase Factors
DS	–	Deterministic Software
FC	–	Fuel Channel
FE	–	Finite Element
FOSM	–	First Order-Second Moment
FORM	–	First Order Reliability Method
GDH	–	Group Distribution Header
IS	–	Importance Sampling,
LOCA	–	Loss of Coolant Accident
LWC	–	Lower Water Communication
MCC	–	Main Cooling Circuit
MCP	–	Main Circulation Pump
MCS	–	Monte Carlo Simulation
MDBA	–	Maximum Design Basis Accident
MSRV	–	Main Steam Relief Valve
NPP	–	Nuclear Power Plant
PS	–	Probabilistic Software

PWR	–	Pressurized Water Reactor
RBMK	–	Russian abbreviation for “Large-power channel-type reactor”
RC	–	Reinforced Concrete
RS	–	Response Surface
SDH	–	Steam Distribution Header
SDD	–	Steam Distribution Device.

1
Introduction

Concrete is one of the most popular materials for buildings because it has high compressive strength, flexibility in its form and is widely available. The history of concrete usage dates back to over a thousand years. Concrete is the principal choice of material for the construction of large civil engineering structures. The developed world has demonstrated its faith in the material by choosing concrete for the main structures of industrial and chemical plant as well for transport, water and energy-related infrastructures [1]. However, concrete has limited tensile strength, which is only about ten percent of its compressive strength, whereas zero strength after cracks develops. In the late nineteenth century, reinforcing materials, such as iron or steel rods, began to be used to increase the tensile strength of concrete. Today steel bars are used as common reinforcing material. Reinforced concrete became the most important building material and is widely used in many types of engineering structures. The economy, the efficiency, the strength and the stiffness of reinforced concrete make it an attractive material for a wide range of structural applications. Reinforced concrete structures are widely used in nuclear energy plants. Reinforced concrete structures play an important role in the economic and social fabric of many countries and are required to perform their function with integrity and reliability for long-term serviceability in the case of nuclear safety related structures. Usually steel bars have over 100 times the tensile strength of concrete, but the cost is higher than that of concrete. Therefore, the most economical solution is when concrete resists compression and steel provides tensile strength. Also it is essential that concrete and steel deform together and deformed reinforcing bars are being used to increase the capacity to resist bond stresses.

Advantages of reinforced concrete can be summarized as follows [2]:

- It has a relatively high compressive strength;
- It has better resistance to fire than steel or wood;
- It has a long service life with low maintenance cost;
- In some types of structures, such as dams, piers, and footing, it is the most economical structural material;
- It can be cast to take any shape required, making it widely used in precast structural components.

Disadvantages of reinforced concrete can be summarized as follows:

- It has a low tensile strength (zero strength after cracks develops);
- It needs mixing, casting, and curing, all of which affect the final strength of concrete;
- The cost of the forms used to cast concrete is relatively high. The cost of the forms used to cast concrete is relatively high;
- It has a lower compressive strength than steel (about 1/10, depending on material), which requires large sections in columns of multi-story buildings;
- Cracks develop in concrete due to shrinkage and the application of live loads.

The economy, the efficiency, the strength and the stiffness of reinforced concrete make it an attractive material for a wide range of structural applications. For its use as a structural material, concrete must satisfy the following conditions [3]:

- The structure must be strong and safe. The proper application of the fundamental principles of analysis, the laws of equilibrium and the consideration of the mechanical properties of the component materials should result in a sufficient margin of safety against collapse under accidental overloads.
- The structure must be stiff and appear unblemished. Care must be taken to control deflections under service loads and to limit the crack width to an acceptable level.
- The structure must be economical. Materials must be used efficiently since the difference in unit cost between concrete and steel is relatively large.

One of the main requirements for reinforced concrete building structures is that during extreme internal and/or external loading, the structural integrity of the buildings and components installed in the building should be retained. The design or structural integrity analysis of complex building structures are a sophisticated task. Analytical solutions and sophisticated numerical models are used to evaluate the structural integrity of these structures. The development of analytical models for the response of the reinforced concrete structures is a complicated task. Difficulty of the analysis of reinforced concrete structures is related with the following factors [4]:

- Reinforced concrete is a composite material made up of concrete and steel, two materials with very different physical and mechanical behaviour;
- Concrete exhibits non-linear behaviour even under low level loading due to non-linear material behaviour, environmental effects, cracking, biaxial stiffening and strain softening;
- Reinforcing steel and concrete interact in a complex way through bond-slip and aggregate interlock.

Accordingly, the analysis of reinforced concrete structures using classical analytical methods is complicated for reliability of the results and experimental studies are costly. Advanced sophisticated numerical tools can be an indispensable aid in the assessment of the safety and serviceability of reinforced concrete structures. This is especially true for many complex modern structures, such as nuclear power plants, bridges, off-shore platforms for oil and gas exploration and underground or underwater tunnels, which are subjected to very complex load histories. The safety and serviceability assessment of these structures necessitates the development of accurate and reliable methods and models for their analysis. Moreover, it should be noted that the transient behaviour of the structures during transient loading is a complex phenomenon due to various factors, such as inertia effects, large deformations, and inelastic behaviour. It is, thus, not possible to obtain analytical solutions for general cases; so sophisticated numerical models are necessary for the analysis. The most popular method for the advanced analysis of complicated structures is finite element method [5, 6]. It is a general method of structural analysis in which the solution of a problem in continuum mechanics is approximated by the analysis of an assemblage of finite elements which are interconnected at a finite number of nodal points and represent the solution domain of the problem. Applications range from the stress analysis of solids to the solution of acoustical phenomena, neutron physics and fluid dynamic problems. The finite element method is established as a general numerical method for the solution of partial differential equations subject to known boundary and initial conditions. In the case of linear analysis, the finite element method is widely used as a design tool [7]. In solving the problems of non-linear analysis, the use of the method depends on two major factors. First, the increase in computational effort required for non-linear problems necessitates that considerable computing power was available to the designer at low cost. The second major factor is related to the level of complexity of non-linear analysis.

Nowadays the finite element method (FEM) has been extensively used to simulate many applications in structural dynamics [8 - 12]. Finite element codes are able to accurately model the plastic deformation via bending, compression or full collapse of the structures. After the terrorist attacks in New York and Washington D. C. using commercial airliners, the structural integrity assessment of civil airplane crashes into civil structures has become very important. During the recent years the researchers from many countries have been simulating aircraft crashes to building structures. The FEM methodology was mainly used for the aircraft crash analysis [13 - 17].

Due to the tendency of increased nuclear safety, the analysis of transient loading will demand multidisciplinary optimization of the methods used. However, simulation-based multidisciplinary optimization generates deterministic optimum design, which is frequently pushed to the limits of design constraints boundaries, leaving little or no room for tolerances (uncertainty) in modelling, simulation uncertainties, and manufacturing imperfections. Consequently, deterministic optimum designs that are obtained without consideration of uncertainty may result in unreliable designs, indicating the need for Reliability-Based Design Optimization [18].

In structural integrity analysis of the buildings it is very important to evaluate uncertainty associated with loads, material properties, geometrical parameters, boundaries and other parameters [19]. This can be resolved using probabilistic analyses methods [20, 21]. Therefore, a probability-based structural integrity analysis was performed as the integration of deterministic and probabilistic methods using existing state-of-the-art software for both the whipping pipe event and the aircraft crash event.

The methodology of the deterministic structural integrity analysis of the reinforced concrete structures using finite element method and methodology probability-based structural integrity analysis that integrates deterministic and probabilistic methods is explained in this book. The application of these methodologies to Ignalina Nuclear power plant (NPP) for postulated accidents is presented as examples.

The Ignalina NPP has a RBMK type reactor that is quite different in comparison to the power plants with PWR or BWR type's reactors. Several events have been identified for these plants that can compromise the integrity of critical structural components. The Chernobyl RBMK reactor accident is the most serious accident in the history of the nuclear industry. Typically, RBMK reactors do not possess the conventional containment structure. Only Ignalina NPP contains two RBMK 1500 reactors, which are the most advanced version of the RBMK reactor and have a pressure suppression type confinement, which is referred to as the Accident Localisation System (ALS) [22]. However the ALS encloses only about 65% of the entire cooling circuit. It does not enclose the sections of piping most vulnerable to rupture in case of the dangerous loss-of-coolant accident. The structures of ALS are very important system to nuclear power plants safety not only during operation, but also when it is shutdown. The fuel is located in the pools of ALS during shutdown. The unloading of the fuel after shutting down the reactor takes several years. Therefore, for the reliability of the analysis of these structures, deterministic and probabilistic methodologies of the structural integrity analysis were used.

The finite element method is used for deterministic strength analysis of the reinforced concrete structures. The deterministic finite element software NEPTUNE [23] was used here for structural integrity analysis. This software can analyze the transient structural response of the concrete and steel structures, which undergo large displacements and non-linear material response in case of transient loading, including object impact onto the structures.

The ProFES [24] software was used for the probabilistic analysis of structural failure. ProFES is a probabilistic analysis system that allows performing probabilistic finite element analysis in a 3D environment that is similar to modern deterministic finite element analysis.

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