Focused on Fracture Mechanics in Central and East Europe

Methodological developments in the field of structural integrity analyses of large scale reactor pressure vessels in Hungary

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ABSTRACT. Buildings, structures and systems of large scale and high value (e.g. conventional and nuclear power plants, etc.) are designed for a certain, limited service lifetime. If the standards and guidelines of the time are taken into account during the design process, the resulting structures will operate safely in most cases. However, in the course of technical history there were examples of unusual, catastrophic failures of structures, even resulting in human casualties. Although the concept of Structural Integrity first appeared in industrial applications only two-three decades ago, its pertinence has been growing higher ever since. Four nuclear power generation units have been constructed in Hungary, more than 30 years ago. In every unit, VVER-440 V213 type light-water cooled, light-water moderated, pressurized water reactors are in operation. Since the mid-1980s, Pressurized Thermal Shock (PTS) analyses of Reactor Pressure Vessels (RPV) have been conducted in Hungary, where the concept of structural integrity was the basis of research and development. In the first part of the paper, a short historic overview is given, where the origins of the Structural Integrity concept are presented, and the beginnings of Structural Integrity in Hungary are summarized. In the second part, a new conceptual model of Structural Integrity is introduced. In the third part, a brief description of the VVER-440 V213 type RPV and its surrounding primary system is presented. In the fourth part, a conceptual model developed for PTS Structural Integrity Analyses is explained.

KEYWORDS. Structural Integrity; Structural Integrity Analyses; Reactor Pressure Vessels; Pressurized Thermal Shock; Methodology.

INTRODUCTION

Buildings, structures and systems of large scale and high value (eg. conventional and nuclear power plants, chemical plants, gas and oil processing plants, long-distance energy transfer pipelines, bridges, airplanes, ships, etc.) are designed for a certain, limited (generally 15-30-50 years) service lifetime, taking the standards and guidelines of the era into account. These standards (eg. the ASME Code [2], the KTA Standards [49], and the VDI Standards [102]) and guide-lines (eg. PNAE [83], VERLIFE [104]) reflect the scientific and technological level of the previous years or decades. If they are taken into account during the design process, the resulting structures will operate safely in most cases. However, in the course of technical history there were examples of unusual, catastrophic failures of structures, even resulting in human casualties, e. g. the sinking of the Titanic, then the serial accidents of the Liberty-type ships, all of which happened in cold maritime conditions. In Hungary, there happened a catastrophic accident of a Carbonic acid processing plant on January 2, 1969. The weather had been particularly cold for several weeks at the time. On that day, one of the plant's large-scale pressure vessels operating under high pressure failed by brittle fracture. The accident killed 9 people and there was substantial property damage as well. At any rate, it cannot be said with absolute certainty that any kind of unusual conditions will not occur in the future. It is for this reason that the risk of catastrophic consequences needs to be minimized.

In the history of pressurized water nuclear power plants, there were severe accidents at Three Mile Island (1979) and Rancho Seco (1978), both ranked in category 5 on the internationally recognized IAEA scale. These events caused no human casualties; they, however, had severe technical, material and safety consequences. Along with other casualties not listed here, the conclusions of these incidents played a significant role in forming the concept of Structural Integrity, evolving into a relatively independent scientific research field with a high practical relevance.

As it was stated above, the standards (e. g. the ASME Code [2], the KTA Standards [49], and the VDI Standards [102]) and guidelines (e. g. PNAE [83], VERLIFE [104]) applied during the design process of a large-scale structure reflect the scientific and technological level of the previous years or decades. But, as known from general experience, these standards and guidelines are evolving over time, and the goals, requirements may also change during the service time of equipments. Therefore, the context of safe operation is part of an advancing world, where the meaning of safety, however, must remain constant. Its actual expression needs to be adapted to the changing context. Consequently, for instance when a new safety requirement comes into effect, the safety calculations need to be completed as soon as possible. That is the reason why the methodologies of calculations also evolve with time. Therefore, it makes sense to define a high-level, abstract conceptual model of Structural Integrity using results from theoretical computer science that will help demonstrate the evolutionary character of the work that has been done during the last three decades in Hungary.

The origins of the Structural Integrity Concept

Although the concept of Structural Integrity first appeared in industrial applications only three-four decades ago, its relevance has been growing higher ever since. Despite being a relatively young field of study, its formation started more than a hundred years ago. In 1921, Griffith [36] published the fundamental concept that underlies the modern theory of linear elastic fracture mechanics. His theory was based on a long series of experiments, theoretical stress analyses and the synthesis of his preceding work. Griffith's fracture theory approaches the subject with an energetic attitude. The reason why his work could not spread widely in practice is that strictly speaking, it only applies to glass-like brittle materials. Also, he determined the fracture behavior of a system by analyzing its energy-balance, which was an unfamiliar method for the engineering community at the time.

During the 1930s, Hungarian-born Egon Orowan (Orován Ede) began to examine the theory's applicability for metals [61], and for the following two decades, he dedicated himself to developing the model describing the fracture behavior of metals. In the mid-1940s, he realized that even in the case of brittle behavior, plastic deformation plays a significant role [64], [65]. The synthesis of his results was published in 1952 [70]. Orowan's theory –similar to that of Griffith's– holds an energetic approach [72]. In addition to improving the fracture theory of metals, Orowan greatly contributed to the scientific description of their micro-structure [62], the processes operating on micro-scale [71], as well as explaining the phenomenon of creep [66], [69], and fatigue [63]. He also conducted a series of remarkable experiments [68], [74]. His works in which he explains the relations between the micro- and macro-scale behavior of materials (e. g. strength), are equally of high relevance [67], [71]. One of his most influential publications –both for the engineering community and for the evolution of Structural Integrity as a concept– was the book chapter 'Strength and failure of materials' [73], which he wrote for the Kellogg Company. In this review intended to aid engineers designing piping systems, he summarizes the basics of strength of structural materials and their possible failure mechanisms in a particularly concise and compact manner. His ideas written in this document are valid to this day. It is for this reason that he can be considered one of the establishers of the field of Structural Integrity.

In the late 1940s, George Rankine Irwin –based on experimental and theoretical studies– concluded that plasticity occurring around the crack tip plays a relevant role in regulating the fracture behavior of brittle metallic materials [41]. His research and results were independent from those of Orowan's. During the 1950s, Irwin revised the Griffith theory; he suggested modifications, generalizing the original one to quasi-brittle materials. In his landmark paper, published in 1957 [42], Irwin reformulated the Griffith theory in terms of singular expansions of stresses around the crack front, and proved that his approach was equivalent to Griffith's approach; that is, he introduced a new 'complementary view' [84] on the fracture problem. This judgment proved to be a stroke of genius. Through the description Irwin had chosen, he introduced the concept of *Stress Intensity Factor* (SIF), which enabled engineers to perceive the fracture problem *in their own categories of thinking* (i.e. in the language of stresses) [32]. This presented a more understandable description of fracture to them. His ideas initiated the decisive progress in fracture mechanics as a new scientific discipline, and a powerful tool applicable to numerous engineering problems connected with e.g. safety analyses of critical components of various engineering structures. Likewise Orowan, Irwin also promoted research regarding various aspects of fracture mechanics. He also gave much attention to the development of new test methods, e.g. the determination of the characteristics of crack-growth resistance of structural materials.

In recognition of Griffith's, Irwin's and Orowan's essential contributions to fracture mechanics, the fundamentals of the field are nowadays called the Griffith-Irwin concept [106], or Griffith-Irwin-Orowan theory [105].

While Irwin's theory became widely known, the energetic approach to fracture mechanics improved significantly as well. The concept of the *J-integral* was developed in 1967 by Cherepanov [13] and in 1968 by Rice [86] independently, who showed that the energetic contour–path integral (the J-integral) was independent from the path around a crack. Their work was based on Eshelby's seminal work [24, 25].

The field of Fracture Mechanics improved rapidly ever since the J-integral emerged nearly five decades ago, and the improvement has been continuing to this day. Numerous efforts have been made in attempt to generalize the concept of the J-integral (in particular, Maugin's work was highly remarkable [55-58]). New models and theories emerged, such as Gillemot's Absorbed Specific Fracture Energy (ASFE) Theory [34, 35, 8, 9]; the Strain Energy Density Theory developed by Sih [90, 8]; numerous local approach models [44], for instance the Beremin model and its different generalizations [6], [7, 11, 12, 38, 39]; the Margolin model [52-54]; Gurson's model of ductile damage [59]; as well as different multi-scale models [80-82]. The list of these examples is not nearly complete. In general, it can be said that these theories are in the phase of development rather than completion. The relatively small numbers of experimental evidences, as well as the necessity to be familiar with modern theoretical methods of material science in order to comprehend these ideas are reasons why they are not widely applied to engineering problems. Their application is confined only to particular cases so far. Their review exceeds the frame of present study.

The beginnings and evolution of the Structural Integrity Concept in Hungary

Disseminating the notion of Fracture Mechanics, as well as introducing the concept of Structural Integrity and developing the theory for industrial applications began at the turn of the 1950s and 60s in Hungary. A great contributor to the theory of Fracture Mechanics was L. Gillemot; he developed the Absorbed Specific Energy Till Fracture model (ASPEF) (or named synonymously Absorbed Specific Fracture Energy model - ASFE) and conducted internationally recognized researches with fellow colleagues E. Czoboly, I. Havas, F. Gillemot, I. Artinger and others at the Budapest University of Technology and Economics. Furthermore, P. Romvári and his associates L. Tóth, J. Lukács, Gy. Nagy and others at the University of Miskolc were notable researchers of Fracture Mechanics and its industrial applications. L. Tóth organized a series of international 'Fracture mechanics seminars' starting in 1981, aspiring to spread the recognition of the field of fracture mechanics and its primary field of application, Structural Integrity.

Starting in the early 1960s, there emerged several independent, non-academic researches for the industrial applications of the concept of Structural Integrity. They can be considered the forerunners of applying the Structural Integrity concept in Hungary. The first units of higher capacity fossil power plants were built in these times with a unit power of 50-100 MW; working with initial thermodynamic parameters (T_{init}> 500 °C, p_{init}> 100 bar). From the late 60's, twelve blocks with a unit power of 220 MW, initial thermodynamic parameters (T_{init}= 575 °C, p_{init}= 172 bar) were built, based on fossilized primary energy resources (lignite, oil and gas). These new, high-performance units operating with immense parameters required equipments of a much larger scale than before. The calculations for designing these new equipments inevitably demanded a more accurate model than those in the standards of the time. In the office commissioned to design the power plants (ERŐTERV), J. Fekete derived a method suitable for analyzing the behavior of three dimensional elastic pipelines based on the ideas of the finite element method; he applied Castigliano's theorem of the Mechanics of Continua [26, 28]. He also developed the computer implementation for solving the problem numerically, and utilizing this software he successfully completed the analyses of pipelines during numerous industrial design processes [27, 29]. Taking the very high operational temperature into account, the phenomenon of creep was also considered throughout the calculations.

During the late 1960s, F. Kolonits determined the stress fields forming through the walls of VVER-440 type reactor blocks of nuclear power plants both in steady-state and during transient operating conditions. [45-48]. It can be remarked that in certain routines, the algorithms developed for these analyses operated with more sophisticated mathematical methods than those implemented in the VISA-II code (which was in general use for the probabilistic fracture mechanical analyses of reactor pressure vessels in the late 1980s.) [91]. It did not contain any Fracture Mechanics routine, however.

Beginning in the middle of the 1960s, a background organization of the Hungarian electric industry, the Electric Power Industry Research Institute housed a research of large scale equipments in power plants led by G. Szabolcs [95]. Starting in the late 1970s, they conducted a long-term R&D work that resulted in a program suitable for solving three dimensional thermo-mechanical problems of power plant structures [75-77, 79, 92-94, 97]. The program was fit to solve problems of

linear elasticity, as well as more complex ones considering plastic deformation, creep and fracture mechanics. Later Z. Pammer upgraded the program with the 'p-extended FEM' technology [78]. In the late 1980s, G. Szabolcs developed a code suitable for the Pressurized Thermal Shock analysis of reactor pressure vessels of nuclear power plants [96].
Since the beginning of the 1990s, PTS analyses of reactor vessels of nuclear power plants have been conducted by the MTA KFKI AEKI, then later its legal successor, the MTA EK where the concept of structural integrity was the basis of the research. Starting in the middle of the 1990s, the Bay Zoltán Institute (BZI) in Miskolc has been making significant improvements in the field of structural integrity and its applications, first led by L. Tóth. His work has been continued by his successors, Gy. B. Lenkey and Sz. Szávai. With fellow colleagues, they have accomplished notable achievements in the research of structural integrity. These teams have been working in close co-operation since the early days of BZI.
In the next paragraph, some notes are made to the concept of structural integrity; afterwards the developments made in the PTS safety analyses methods of reactor pressure vessels of nuclear power plants are presented.

NOTES TO THE CONCEPTUAL MODEL OF STRUCTURAL INTEGRITY

Before going into the detailed explanation of the main subject of the paper, it is important to discuss the notion of Structural Integrity very briefly. In these days it is difficult to give a concise, unambiguous definition to Structural Integrity, as it incorporates many aspects of the complex problematics of designing and safely operating large-scale and high-value engineering systems.
Structural Integrity refers to a field of engineering science that deals with the assessment of engineering structures to work under various conditions without catastrophic damage (e.g. brittle fracture, tearing or collapsing). Methodologies based on the structural integrity concept include studies of normal operation conditions and of accidental situations that have previously occurred or are likely to occur at or above a certain risk level, in order to prevent failures in the future.
Structural Integrity is the term used for the load carrying characteristic of a solid system, designed for certain technological and economic functions. Structural integrity is the ability of the system to hold all technological aspects together that serve the goals of the designed function, assuring that the construction will continuously perform, during normal use and also accidental situations which are likely to occur at or above a certain risk level, for at least the designed lifetime of the system. Equipments are constructed having regard to the concept of structural integrity to ensure that catastrophic failure does not occur, which could result in human injuries or even casualties, severe damage, and ecological as well as economical losses.
According to the ESIS definition, '*Structural Integrity… refers to the safe operation of engineering components, structures and materials, and addresses the science and technology that is used to assess the margin between safe operation and failure*' [23].
Structural integrity –as a scientific field– includes a general understanding of various applicable theories/disciplines of the subject (e.g. fracture mechanics, thermomechanics of continua, material science, computational material science, numerical mathematics, measurement science etc.), as well as other practical and theoretical methods (e.g. simulation methods, material testing methodologies, nondestructive testing procedures etc.). These tools, however, are not effective independently; yet when applied in a proper combination, they become a problem-solving model distinctive to this field, through the synergistic interactions that are present between these various disciplines. In this sense, as stated by Kuhn [50], Structural Integrity can be regarded as a special *scientific-engineering paradigm*. An essential quality to this field is its interdisciplinary character. The constant developments of background-studies, as well as the increasing demand for improved industrial and environmental solutions consequently make it a rapidly progressing subject. The relevant aspects of Structural Integrity –from a scientific point of view, according to Lukács– are demonstrated on Fig. 1 [51]. The different aspects are represented by the faces of a tetrahedron, each face bordered by edges which meet in vertices. These four vertices are each assigned a conceptual category (for instance the database of materials/properties, etc.). Quoting Lukács, the model is named the 'Structural Integrity Tetrahedron' [51].
According to Fig. 1, when analyzing a structure's integrity, three key aspects need to be considered particularly, listed here:

- Analysis aspect, which aims to determine and evaluate the state of the structure by calculations, during which the following conditions need to be taken into account:
    - Distribution of existing and hypothetical flaws in terms of size and position,
    - Time evolution of loading and environmental factors;
    - State of structural materials and their evolution in terms of time (description of ageing).
- Experimental aspect, which provides data for the analysis based on experiments/measurements

  - o Non-destructive examinations, which provide data about the distribution of flaws detected during the tests, in terms of size and position; furthermore, they are meant to verify the compliance of these discontinuities with the flaws postulated in calculations;
  - o Material tests, which provide relevant data for the analysis, taking material ageing into account as well;
  - o Experimental stress-analyses, which verifies the stress-values calculated by the model calculations.
- – IT aspect, which assists the implementation of the analyses by completing the following tasks:
  - o Collecting and recording data of loads and environmental factors; storing these data in appropriate databases;
  - o Selecting and storing particular parameters of materials needed for the analyses;
  - o Executing the calculations; recording and storing the results.

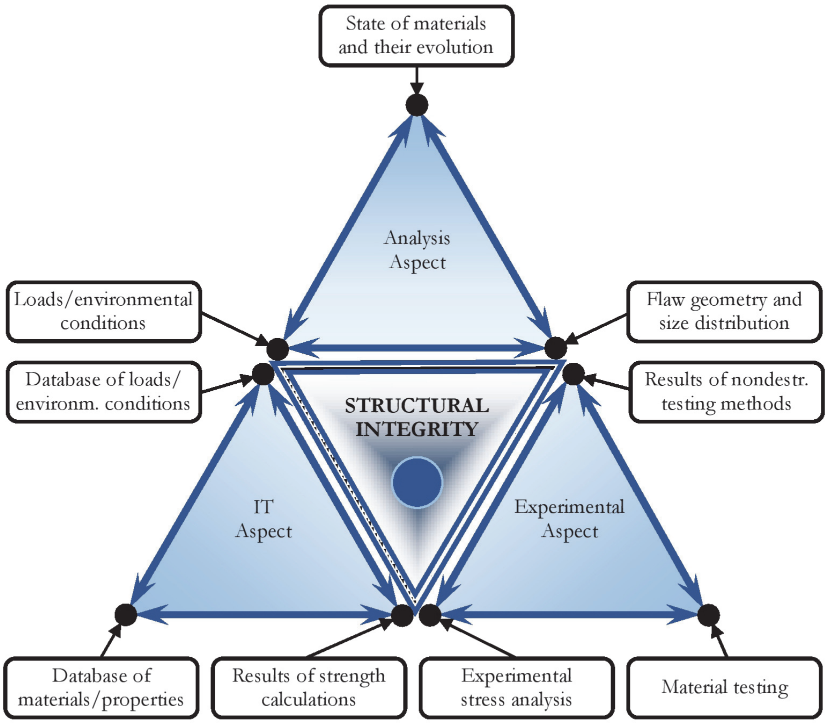

Figure 1: The faces of the 'Structural Integrity tetrahedron'. Conceptual model of Structural Integrity after Lukács [51] p. 200.

On Fig. 1, the vertices represent the key aspects listed above; the edges of the tetrahedron indicate an existing connection between certain parameters. Adjacent vertices indicate a strong, and in most cases, synergistic connection between two parameters. While the tetrahedron model of structural integrity is particularly illustrative, by using abstract mathematical tools, we developed it to be a model capable of describing the concept of structural integrity on a highly abstract level as well. It can also be implemented when designing the structural integrity analysis project of an actual structure. By developing this abstract model, we intended to aid the comprehension of the general conceptual model; also to point out how to formulate the development of a scientific, or even industrial structural integrity project on a certain level; and to simplify the comparison of different models and methods.

The abstract model is based on the theory of graph-transformation systems, which describes complex information-technological systems (hardware and software). This theory was developed based on the notion of so-called graph-transformation systems [21]. Graph-transformation systems are based on the concept of graph grammars [20, 88], which were an advancement of formal languages used for programming computers and today for IT systems and applications (see e. g. Chomsky [14-16], Révész [85]). Since their emergence nearly four decades ago, graph grammars have been constantly improving. Today they are also used as tools for developing applications in the IT area in the specification phase [1, 4, 17-19, 22]. Publications [1] and [17] give a concise introduction to graph-transformation systems.

In essence, the abstract model was created by these steps: the unfolded tetrahedron on Fig. 1 was transformed into a three-dimensional tetrahedron, and the edges were merged in global view. The 'nodes' at the vertex corners, however, are not zero-dimensional formations; they have an inner structure and inner dimension. Thus, they are hyper-nodes;

moreover, the edges are hyper-edges, which link to hyper-nodes through appropriately defined interfaces and connectors. Each hyper-node and hyper-edge has its own type. In this manner, the tetrahedron of structural integrity transforms into a typed hyper-graph, demonstrated on Fig. 2. On Fig. 2, the inner structures of hyper-nodes are shown in zoomed-in illustrations. Each outer hyper-node is assigned an abstract label (in this case a Greek letter), in order to keep the hyper-nodes identifiable without explaining their inner structure. Inside the hyper-nodes, the connections between different conceptual categories are represented by the following: the categories themselves are the inner hyper-nodes, and the connections are the inner hyper-edges and their relations. The above-mentioned inner nodes are also assigned a label, marked with an upper-case letter. The foregoing explanation, in essence, means that the hyper-nodes of the tetrahedron themselves are labeled hyper-graphs [18, 88].

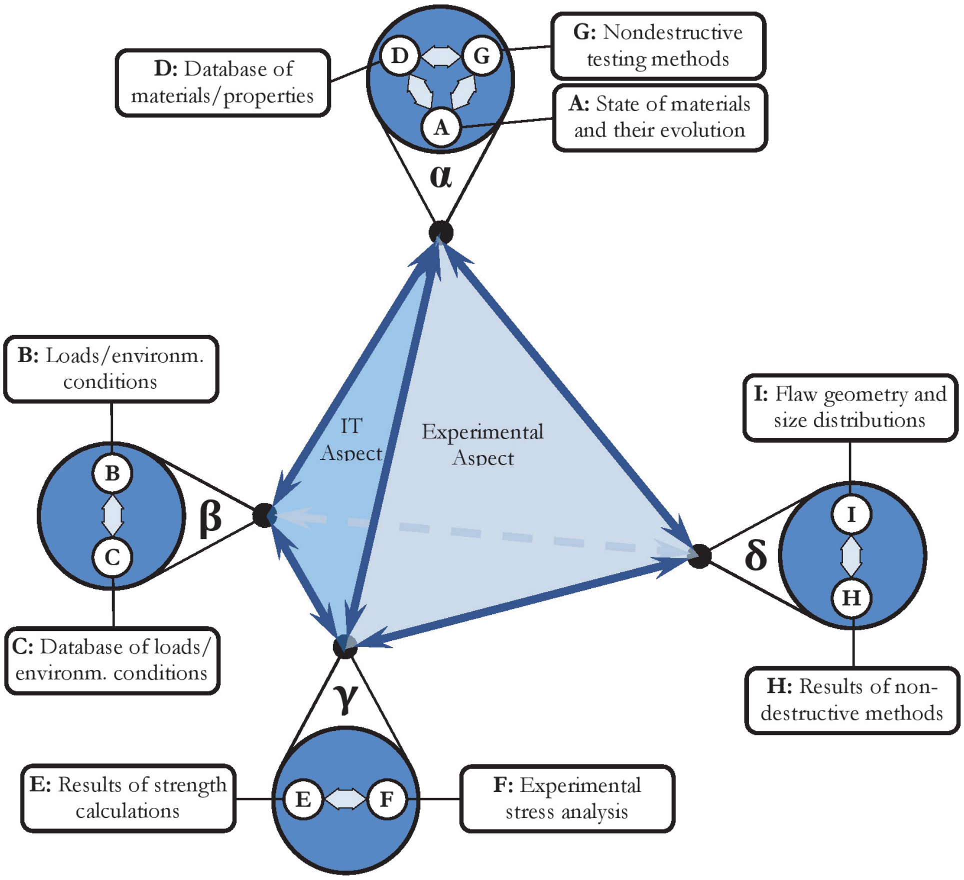

Figure 2: The Conceptual model of Structural Integrity. The hypergraph model of the 'Structural Integrity tetrahedron'.

In a properly generalized form, the model is suitable for e. g. describing the steps of methodical development in structural integrity analyses; for in the past four-five decades, the methods of structural integrity analyses have been improving rapidly and constantly [31]. The structural integrity analysis of a certain project or system is completed having regard to the standards, guidelines and recommendations being in effect at the time. However, there stands a possibility for it to be completed based on methods beyond the standards; as these methods are usually improving significantly faster. In these cases, it is particularly important to indicate where and how the new method differs from the previously accepted method, and also where the differences appear in the results. The extended model is based on the concept and method of typed graph transformation systems. In essence, the graph representing the type of the system is defined on the higher level. On the lower level, instance graphs are placed. Instance graphs can only be graphs that fulfill the definitions established by the type graph. Note that this allows the instance graph to be more refined than the type graph (that is, to contain more information or have a more detailed structure), but each instance graph must inherit all features and rules defined by the type graph. The evolution of a system described by graphs (e. g. evolution over time) is determined by the so-called graph transformation rules [20-22]. In the case of the structural integrity tetrahedron, the specific graph is a hyper-graph; thus its transformations are defined by hyper-graph transformation rules [18, 88].

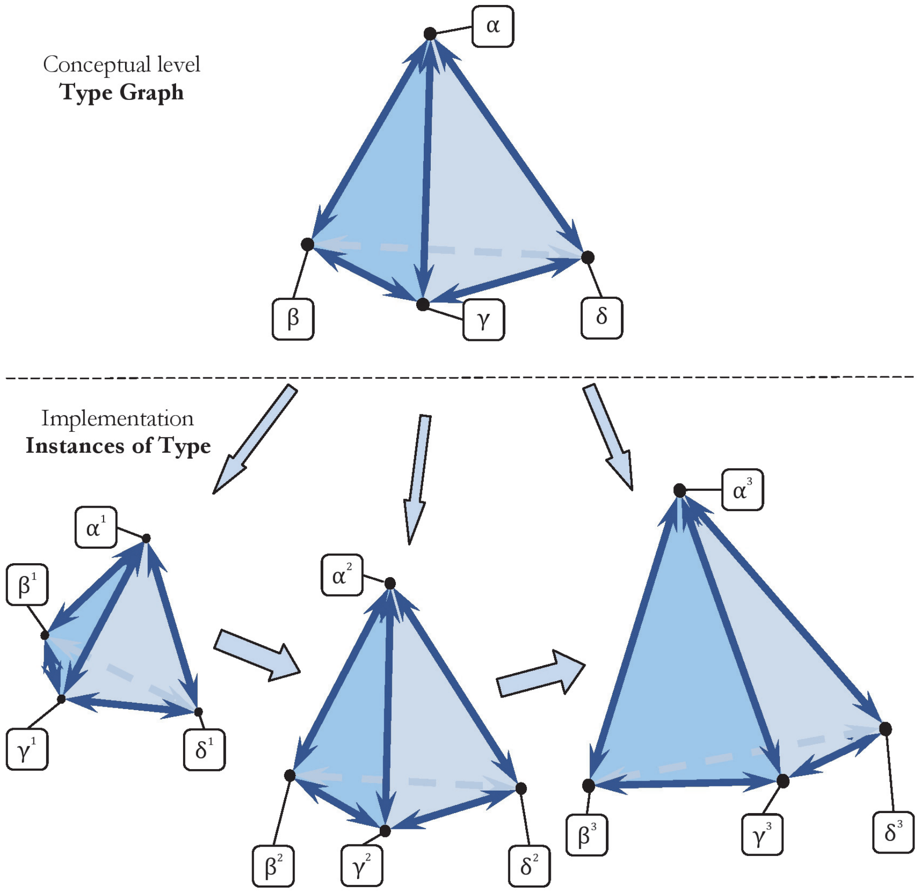

Figure 3: Conceptual model of Structural Integrity and evolution of various implementations based on the hypergraph model.

On Fig. 3, the growth model of systems fulfilling the above-stated definition of structural integrity is shown. The figure indicates the possible evolution of structural integrity systems on an abstract level. We postulate that the type graph of the transformation system is the conceptual hyper-graph shown on Fig. 2. The implemented systems can only be ones that have a graph compatible with the type graph, for that can only inherit features defined by the type graph. (To simplify our expressions, hereinafter hyper-graphs are named graphs.) Illustratively, the above-explained relation means that the type graph defines the 'skeleton' of the implemented systems at instance level. For the past years in our institution, developments have been made meeting the requirements determined by this abstract model [30].
In the following, we concentrate on the analytical and computational aspect of structural integrity. We give an overview of the developments made in the area of structural integrity analyses of large-scale nuclear power plant reactor pressure vessels, and the methods elaborated for safety calculations during the past three decades in Hungary.
When discussing the subject, the above-presented aspects are taken into account. The developed methods/models are presented in a manner that it is clear how they comply with the conceptual model of structural integrity. Also, the differences, similarities and individual features of each model will be discussed.

DESCRIPTION OF THE SYSTEM SUBJECTED TO PRESSURIZED THERMAL SHOCK ANALYSES

From now on, we will focus on the subject of Pressurized Thermal Shock (PTS) analyses of Reactor Pressure Vessels (RPVs) operating in Hungary. PTS calculations are typical applications of the Structural Integrity concept, as they are concerned with studies of accidents that may occur in the primary circuit of a Nuclear Power Plant (hereinafter NPP), at or above a certain risk level; these calculations are completed in order to prevent the structural failure of an RPV. At the design stage, PTS calculations serve to assure the design service lifetime. In the case of operating equipments the aim of the PTS analysis is to confirm its more realistic allowable service time. At first, a short introduction of the equipment and its surrounding system is given.

The Reactor Pressure Vessels in Hungary

Four nuclear power generation units were constructed in Hungary, at Paks NPP, between 1976 and 1987. In every unit, VVER-440 type light-water cooled, light-water moderated, pressurized reactors are in operation; the type of their RPVs is VVER-440/V-213Cs. These systems belong to the second generation of pressurized water reactors. The RPVs were manufactured in the Škoda Machinery Plant, Plžen, Chech Republic (at that time, Czechoslovakia).

The VVER-440/V-213Cs RPV consists of seven parts: the flange, the upper and lower nozzle region shells, the upper and lower core region shells, the support shell and the elliptical bottom. These parts are joined to one another with six circumferential welds using submerged arc welding. The resulting equipment has a length of 11800 mm, with its inner diameter ≈3540 mm. All shells are made of forgings from Cr-Mo-V alloyed steel, with a thickness of 140 mm. Plates from this steel were used also to produce the elliptical bottom, with a thickness of 160 mm. The nozzle region shells –with a thickness of 205 mm– each contains six hot and six cold nozzles, which the main coolant pipelines are welded up to. The inner surface of the RPV is protected with anticorrosive cladding, the thickness of which is ≈9 mm. The energetic core has a length of ≈2500 mm; its horizontal section plane has a hexagonal symmetry. The distance between the RPV's inner wall and core baffle is ≈156 mm. The main geometrical dimensions and the shape of the RPV are presented on Fig. 4., where the location of the core is also depicted schematically. The data given above show that the RPV is a large-scale equipment that suffers excessive aging. It is fabricated from a special type of structural material that has BCC crystal-structure at a microscopic level, and shows ductile to brittle transition behavior around a critical temperature at a macro-level. Despite the fact that VVER-440/V-213Cs RPVs were produced in a relatively large series (18-20 vessels were manufactured at Škoda Plžen between 1978 and 1989), each and every one of the RPVs has unique material characteristics that affect the fracture behavior and ageing properties of the given apparatus. In order to monitor the ageing properties of the structural materials, the RPVs have been initially equipped with a surveillance system. High quality In Service Inspection (ISI) systems were installed, starting in the manufacturing phase, followed by regular inspections during operation. The ISI systems have been qualified according to the latest industrial standards.

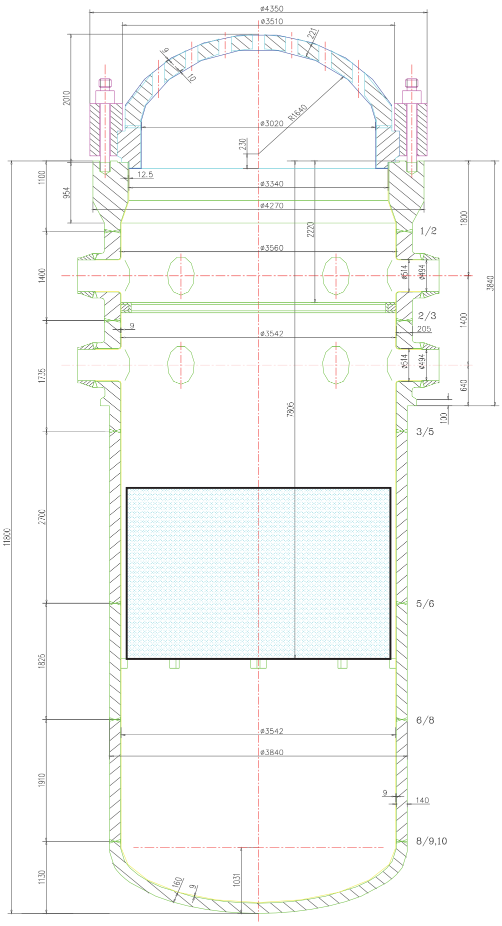

Figure 4: Main dimensions of the pressure retaining part of a VVER-440/V-213 RPV.

The Primary System of VVER-440 Units in Hungary

In order to make the PTS phenomenon more understandable for professionals unfamiliar with the technology, a short overview of the VVER heat generation technology is given below. The VVER 440 type nuclear power systems use light-water: (1) for neutron moderation purposes, and (2) to serve as a medium for energy-transfer between the core and the steam generators. At the core, heat is generated mainly via volumetric processes (thermalized neutrons heat up the water through complex scattering processes at an atomic scale that results in heat at a macroscopic scale), and the heat energy is transported from the primary system to the steam system (secondary system) in steam generators through a surface-dominated process. The steam generators are therefore special large-scale heat-exchangers. The coolant is circulated between the core and the steam generator through large-capacity pipelines, driven by the main coolant pumps. A heat exchanger, together with the pipelines and the main coolant pump comprise one main circulation loop. The VVER-440 technology uses 6 main circulation loops. The RPV, the main circulation loops, and other auxiliary systems comprise the primary system of a unit. The primary system of a VVER-440 type unit is depicted on Fig. 5.

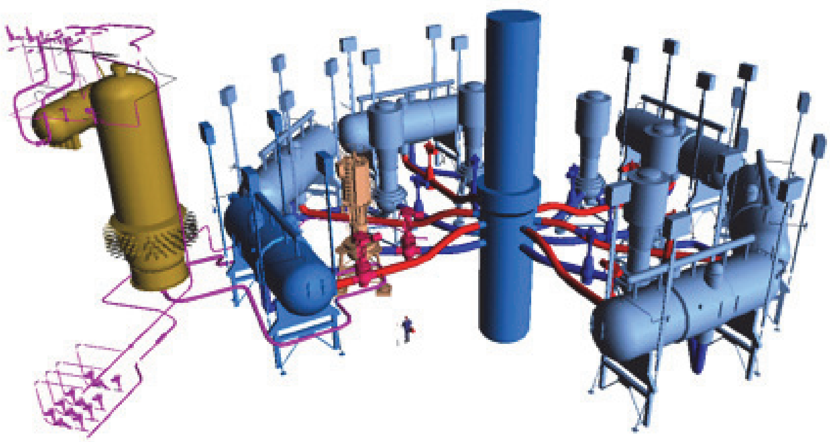

Figure 5: The six-loop structure of a VVER-440/V-213 type NPP unit.

As it can be seen on Fig. 5, the primary system is a very complex object, designed to fulfill the requirements of safe energy generation during *normal operating conditions*, and also in the cases of *anticipated* or *accidental emergency events*.

Normal operating conditions are in cases of different energetic states and operating transients of the reactor, including the start-up and shut-down processes, hydro tests, etc. With normal operation temperature and pressure, the time rates of temperature and pressure changes of the coolant stay within a specified range set by the main designer. During *anticipated emergency events,* pressure and temperature can exceed their values set for normal operating events, and pressure and temperature changes can pass more quickly during transients, but all these values cannot exceed certain limits specified by the main designer. In normal operating conditions as well as during anticipated emergency events, the system is working under controlled circumstances that assure the structural integrity of the primary system and the RPV.

However, the power generating technology, the system temperature, pressure and their changes over the long service time together lead to the structural materials' ageing as a side effect. The primary aging mechanisms taking place in the structural materials of the primary system are: neutron irradiation damage, fatigue, and thermal aging. These mechanisms center around the energetic core of the RPV; furthermore, fatigue and thermal aging can take place in other parts of the system.

As it was previously pointed out, industrial experience and particular cases of catastrophic large-scale structure failures showed that the risk of certain system failures can increase over service time. In unfortunate circumstances, the result can even be a catastrophic failure through a snowball effect. In order to avoid those, structural integrity analyses need to be extended for *accidental* events as well. There has been a demand for these kinds of analyses since the early 1980s, when, from operating experience, it became evident that transients can occur in pressurised water reactors resulting in extreme overcooling that causes thermal shock in the vessel, concurrent with or followed by re-pressurisation. These transients are generally known as Pressurised Thermal Shocks. The unusually high tensile stress caused by thermal shock in the inner vessel wall can cause cleavage initiation of a pre-existing flaw (crack-like defect in a certain dimension). In addition, during operation, neutron irradiation exposure around the energy-generating core makes the RPV material increasingly susceptible to cleavage fracture initiation. Therefore, there is a higher risk of brittle crack initiation during PTS.

METHODOLOGY OF PTS STRUCTURAL INTEGRITY ANALYSES OF VVER-440 RPVS

Overview of the Model of PTS Structural Integrity Analyses

A brief overview of the underlying physical problems of the PTS problem is given next, identifying the core problem of PTS Structural Integrity assessments as the Structural Mechanics problem. Structural Mechanics analysis is the specific subdivision of Structural Integrity seeking to solve the governing equations of the thermal-mechanical problems that describe the phenomenon in the wall of a given RPV. Basic equations of the thermal-mechanics problem are also presented briefly on an abstract, semi-formal level, omitting technical details, in order to make the problem at hand more comprehensible for readers inexperienced in this special field of engineering. Subsequently, some notes will be made to the physical/technological aspects of the problem: the role of neutron physics and thermal-hydraulics in the problem domain, avoiding technical details, as that would exceed the frame of present study. The description will then introduce a problem solving method that has proved successful in many projects worldwide and in Hungary as well [30]. More technical descriptions and details of the problem can be found in [43].

At a conceptual level, the process of solving a PTS Structural Integrity Analysis problem can be divided into three main phases from a Structural Mechanics perspective: (1) Preparatory Phase, during which the effects of material ageing are evaluated in terms of the macroscopic properties of structural materials. At the same time, thermal-hydraulic assessments are performed. (2) Main Phase, when Structural Mechanics calculations are completed, evaluating the response of the system to the loads produced by thermal-hydraulic assessments; (3) Final Phase, where an evaluation of the whole set of results is given in terms of safety or in terms of allowable lifetime.

Next, a short overview of the main tasks comprising the whole project is given.

The Preparatory Phase is divided into two parts: (a) evaluation of the effects of material ageing, and (b) evaluation of the thermo-hydraulic behavior of the system.

To evaluate the consequences of material ageing, one needs to have a thorough understanding of the required control parameters of the ageing mechanisms and the relationships between material parameters and control parameters. The most relevant ageing mechanisms in the case of RPVs are the following: (1) thermal ageing, (2) fatigue and (3) irradiation-assisted ageing. Thermal ageing is the consequence of continuous high temperature, fatigue is caused by changes in the mechanical loadings during the operation of the equipment; the history of temperature and mechanical loading can be extracted from the operating history recorded at the plant, therefore the effect of thermal ageing and mechanical fatigue can be assessed from these data. The evaluation of the effect of irradiation-assisted ageing is more complicated, as neutron fluxes are not measured at the RPV wall directly; however, the neutron-flux field can be reconstructed based on the power history of the core, using neutron-transport calculations developed in the scientific field of neutron physics.

- Neutron physics has a central role during the design and operation of a nuclear power plant, as it is the essential scientific tool that is used for designing and controlling the energy generating core, and also when assessing the 'side effects' of the core. The fuel elements produce neutrons that interact with the surrounding system at various energy levels. Most of the neutrons (the thermalized neutrons) interact with the coolant liquid –at mm order from the neutron source–, and produce heat that is converted into electric energy through a sophisticated energy transport chain. But neutrons with high energy (fast neutrons) can reach locations far from the core, so some of them can interact with structural materials of the RPV wall, causing irreversible changes in their nano- and microstructure, which then leads to irreversible changes in the macroscopic behavior of the materials. This phenomenon is called irradiation assisted ageing. There were early experimental evidences that the changes in the aged material are proportional to the time integral of neutron flux, that is, the neutron-fluence. To make the relation between time, neutron flux, neutron fluence and material parameters quantifiable, it is necessary to assess neutron fluence at relevant locations around the core using *neutron-transport calculations*, as follows:
    - On one hand, to determine the distribution of neutron flux and neutron fluence on the section of the RPV around the core, with regard to the loading history of the reactors; moreover, to estimate the distribution of neutron fluence at the end of the service lifetime, considering the available information on planned fuel element usage and core planning.
    - On the other hand, to assess the distribution of neutron flux and neutron fluence for the specimens placed into surveillance positions, considering the loading history of campaigns during the time of surveillance programs.

  The calculations produce the through wall neutron fluence distribution around the core in the RPV wall, and along the surveillance specimens located at the surveillance system channels around the core, baffle in cases of VVER 440 RPVs. These results serve as essential data for the evaluation of the irradiation assisted ageing effect.

- The evaluation of the effects of material ageing on the behavior of materials requires the characterization of the materials at various ageing stages. The phenomenon of ageing has been known for a long time in cases of operating equipments working in any technological environment; however, to the best knowledge of the author, a precise and predictive theoretical model that describes the phenomenon does not exist yet. Notwithstanding, there are numerous intensive researches focusing on the subject. One of the most promising approaches is the multi-scale modeling of materials, but that is still in a research phase; its use for an industrial Structural Integrity project is not possible at present. Although detailed predictive models for the description of ageing are not available yet, from a more pragmatic engineering perspective, the solution is at hand; various macroscopic imprints of the very highly complex processes of ageing are observable through the experimental characterization of materials, and the behavior of the materials can be described in terms of their macroscopic material parameters in an aged state. As stated above, the most relevant ageing mechanisms in the structural materials of an RPV are: (1) thermal ageing, (2) fatigue and (3) neutron irradiation assisted ageing. Conceptually, all three mechanisms can affect all material parameters required for the analyses –this topic will be discussed next– but experiments showed that significant changes in the parameters were observable during tensile tests and fracture examinations of the structural materials. That is why material ageing programs have concentrated on tensile and fracture characterizations of structural materials at a macroscopic level.

The goal of thermal-hydraulic assessments is to determine the temperature and pressure distribution of the coolant liquid alongside the vessel wall; and the distribution of the heat transfer coefficient between the coolant and the RPV wall during postulated accidents for stress and fracture mechanics analyses. The analyses are divided into two parts:

- Selection of the overcooling sequences; this activity is taking various accident sequences into account including the impact of component malfunctions, different operator actions, internal and external hazards. The selection is based principally on deterministic considerations, but today as a complementary effort, probabilistic PTS sequence selection activities play a significant role during the work.
- Thermal-hydraulic calculations are performed for the above-defined accidental situations. The calculations are based on the following balance equations:
    - Balance of mass, taking the two-phase (liquid-vapor) states of the primary coolant into account as well;
    - Balance of the linear momentum: this is the Navier-Stokes equation or one of its variants in the most general case of CFD calculations;
    - Energy balance, which describes the energetic changes in the liquid during the processes.

  Note that in most cases, simplified models are used during thermal-hydraulic assessments, as (1) full three-dimensional models for the two-phase (liquid-vapor) state of the coolant are currently under intensive research, and (2) CFD models need tremendous IT resources that are unmanageable from an economic aspect in most cases.

In the Main Phase, the solution of the Structural Mechanics problem is achieved by the following steps:

- Heat transfer analyses, during which through wall temperature distributions are determined as a consequence of thermal-hydraulic transients, assuming convective heat transfer between the coolant and the wall, using the classic Fourier heat-equation:

$$\rho c_V \partial_\tau T(x,\tau) + \nabla\left(\lambda \nabla T(x,\tau)\right) = \dot{q}(x,\tau) \tag{1}$$

  using von-Neumann boundary conditions of third kind at the fluid-wall interface, and the state equations:

$$\rho = \rho(T),\ c_V = c_V(T),\ \lambda = \lambda(T) \tag{2}$$

  where x is the space coordinate, τ denotes time, $\partial_\tau = \frac{\partial}{\partial \tau}$ is the time derivative operator, ∇ denotes the spatial gradient operator, T is temperature, $\dot{q}$ is the volumetric heat source density, ρ is mass density, c_v is heat capacity, and λ is the heat conduction coefficient of the structural material.
- Strength calculations to assess the deformation and stress fields, induced by the intensive heat transfer and other mechanical loads during the transient, solving the equation-systems of thermo-elastic (or thermo-elastic-plastic) continua, which are outlined below very briefly:

  The kinematic equation [3, 5, 10, 103]:

$$\varepsilon(x,\tau) = \frac{1}{2}\left(u \circ \nabla + \nabla \circ u\right)(x,\tau) \tag{3}$$

the material (constitutive) laws [3, 5, 10, 33, 37]:

$$d\varepsilon = d_E\varepsilon + d_T\varepsilon + d_p\varepsilon$$

$$d_E\varepsilon = F_E(\sigma_E, T)$$

$$d_T\varepsilon = F_T(\sigma_E, T) \qquad (4)$$

$$d_p\varepsilon = F_p(\sigma_p, T)$$

and the balances:

$$\rho a(x,\tau) + \nabla \cdot \sigma(x,\tau) = f(x,\tau) \qquad (5)$$

$$\sigma^T = \sigma \qquad (6)$$

$$\dot{W}(x,\tau) = \sigma(x,\tau) : \dot{\varepsilon}(x,\tau) \qquad (7)$$

alltogether form the governing equations of the structural mechanics problem that describe the movement of the body in the ambient space; the evolution of the mechanical state of the structure in terms of deformation and stress fields, that are related to each other by the constitutive laws; and the evolution of the strain energy. In the above-written equations, x is the space coordinate, τ denotes time, $\dot{A}$ is the time derivative of A, ∇ denotes spatial gradient operator, d means differential variations of a given quantity, u denotes the displacement vector, ε is the deformation tensor, σ means stress tensor, T is temperature, ρ denotes mass density, a means acceleration, f means the external force densities acting on the body, W denotes the stored energy in the material, · denotes inner multiplication of two vectors, : is inner multiplication of two tensors (multiplication with doubled contraction).
The kinematic equation describes the relation between the deformation of the body and the motion of its 'points' (i. e. small but representative volume elements) in the ambient space. Eq. (3) defines that during PTS Structural Mechanics Calculations, the small deformation theory is used [3, 5, 10, 103].
The balance equations are the following:

- Balance of the linear momentum (5): this balance is called the Cauchy equation of motion that represents Newton's law for continua [5, 10, 37, 57, 58, 103];
- Balance of moment of momentum (6) that assures the symmetry of the stress tensor for continua with classical kinematics [5, 10, 57, 58, 103];
- Energy balance (7), which describes the energetic changes in the material during deformation [10, 103].

The behavior of structural materials is described by the constitutive laws (or constitutive equations) that play an essential role during strength calculations [5, 10, 37, 57, 58, 103]. Since the early days of modern thermodynamics, constitutive equations have played an increasingly significant role in modeling material behavior among various conditions [5, 10, 33, 37, 57, 58, 66, 99, 100, 101, 103]. However, only a few models can be accepted for engineering calculations supplemented with fracture mechanics analyses, for validated strength and fracture mechanics models supplemented with verified material parameters apply to a limited class of constitutive behavior only. At present, only time-independent material models are used, which means that they have no explicit time-dependence; as they depend on time through the values of physical fields (e.g. temperature, fluence) only. From this point, aging also factors in, since materials exhibit changing behavior during long-term operation (normal operation + anticipated emergency events). Material parameters, evaluated in the frame of ageing studies (surveillance programs of individual units or generic ageing research programs) are here connected to the physical/numerical problem solving; these programs supply the required data in the context of the material model selected specifically for the type of the problem at hand. It should be noted, that for the PTS Structural Mechanics problems, the thermo-elastic and thermo-elastic-plastic constitutive behaviors are examined during projects with industrial relevance; according to the best knowledge of the author, application of other, more advanced material models are in a research phase.

- Assessment of material parameters that are not addressed while solving the thermo-mechanics problem, e.g. the calculation of K_{Ic} or J_{Ic} values through the RPV wall.
- Fracture mechanics analyses to assess the stability of detected or postulated cracks in the vessel wall during the transient. Fracture mechanics calculations consist of the steps listed below:
  - Calculation of the crack tip driving forces along, or at distinguished points of the crack front, using:
    - the Stress Intensity Factor concept (K_I) for linear-elastic problems, based on Irwin's works [42], or
    - the J-integral for elastic-plastic problems, based on results of Cherepanov [13] and Rice [86];

$$J = \int_{\Gamma} \left(W\boldsymbol{I} - \varepsilon^{T} \sigma \right) ds \qquad (8)$$

    using the notations of Maugin [55, 56, 58];
  - Assessment of the stability of cracks, in terms of the critical fracture parameters, K_{Ic} or J_{Ic}; these parameters are expressed in the following form:

$$K_{Ic}(T, T_{crit}) = A + B \cdot e^{C(T - T_{crit})} \qquad (9)$$

    in case of the Irwin-model, K_{Ic} is called the fracture toughness of the material; A, B and C are parameters characterizing the material, T_{crit} denotes the critical temperature that characterizes the temperature ranges where brittle or ductile behavior of the material is expected. When $T<T_{crit}$, the material behaves brittle; if $T>T_{crit}$, ductile behavior is expected. During the operation of the equipment, due to ageing, T_{crit} is continuously increasing, thus the material will behave brittler at higher temperatures. ΔT_{crit} is called the shift of T_{crit} that characterizes the ageing process. For the relevant ageing mechanisms discussed above, ageing is formulated in the following forms:

$$\begin{aligned} \Delta T_{crit}^{Th} &= F^{Th}\left(T^{op}\left(\tau\right)\right) \\ \Delta T_{crit}^{Fat} &= F^{Fat}\left(a\left(\tau\right)\right) \\ \Delta T_{crit}^{irr} &= F^{irr}\left(\Phi\left(\tau\right)\right) \end{aligned} \qquad (10)$$

    where ΔT_{crit}^{Th} describes thermal ageing in terms of operational temperature T^{op}; the operational time is τ; ΔT_{crit}^{Fat} describes ageing caused by fatigue in terms of the damage factor a and operational time τ; while ΔT_{crit}^{irr} describes irradiation assisted ageing in terms of neutron fluence Φ and operational time τ.

During the Final Phase, after having the full set of PTS Structural Mechanics solution, the evaluation of Structural Integrity criteria is performed lastly. The RPV is considered safe when all the Integrity criteria are fulfilled. Note that Integrity criteria may contain other aspects beyond physical stability, as Structural Integrity is also a part of the economical/environmental context where these equipments are operating.

Note: the foregoing overview focuses on a very short, semi-formal description of the key steps of PTS Integrity Analyses, in order to make the introduction of the high-level model of the Analysis Methodology possible. Many details were neglected, many known formulas were changed formally to symbolic functions; the intention was to express the fact that the general solution of the problem is not known yet, but there exist many solutions and formulas for particular problems. The formulae can be applied to special problems, but in case of a reflective, abstract description, symbolic descriptions are more effective. Symbolic descriptions are proper tools to organize large sets of information into categories, to demonstrate similarities, differences, and relations between various objects and phenomena. The aim of introducing the symbolic description was to focus on the relevant information at a given level of description; moreover, to restructure the knowledge into manageable pieces, keeping in mind that the integrity of the knowledge must be preserved.

The High Level Model of PTS Structural Integrity Analysis Methodology

As it was shown above, the PTS Analysis problem and its solution methodology is quite sophisticated, as a consequence of the many aspects affecting the results. Although PTS calculations have been part of RPV safety evaluations since the first half of the 1980's, there are various approaches that are analogous in general, but have many differences in details. There exists no internationally recognized standard; there are international guidelines that are recommended to use, (e. g. specifically for VVER units [40] and [104]); also, various approaches are used at a national level in different countries, leading to similar, but somewhat different results in many cases. All of which increases the uncertainty in calculated allowable lifetime results. The situation is complicated by the fact that guidelines are alterable in a sense that they allow using '*more advanced methods*' (i.e. methods that are capable of taking more aspects of the underlying physics into account). However, in this case the analysts are obliged to give proof of the correctness of their method in the context of safety requirements. Nevertheless, analysts have more freedom to choose an approach that is best fit to solve a problem in a given context. That makes the results published by different organizations difficult to compare on an international level [89]. Benchmark exercises calculated in later projects clearly showed that the comparison of results is easier when all relevant aspects of the analyses are clearly described and unambiguously defined; in that case the uncertainty of results reduces significantly [43, 60].

Between 2005 and 2009, within the frame of an international project coordinated by IAEA, an international consensus on good practices for deterministic PTS Structural Integrity evaluations of RPVs has been reached. Results are published in the IAEA-TECDOC-1627 [43], named shortly as 'PTS Good Practices Guide'. This document gives a comprehensive but compact overview on PTS assessments. PTS analysis is typically performed as a series of sequential steps [43], and it is tacitly assumed that the problem-solving procedure follows the strategy shown in the flowchart presented on Fig. 6. This sequential structure is based on the classical staggered problem-solving approach that has been used successfully in engineering and science for a long time. In essence, the approach divides the problem into smaller, relatively independent pieces. At each problem-solving step, the actual task can be solved using the data produced by earlier solution steps.

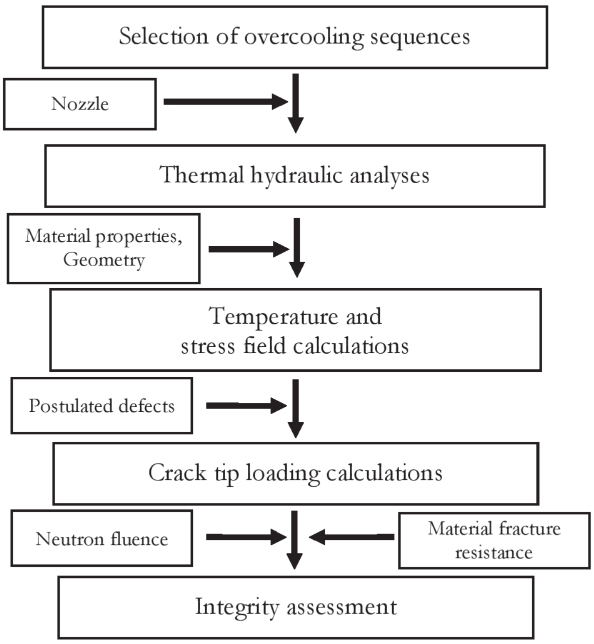

Figure 6: Basic evaluation scheme for PTS Structural Integrity analysis, according to [43].

Although the strategy mentioned above has been widely used in the engineering and scientific community, and there is no reason to disregard it completely, there were reasons to revise the PTS Structural Integrity analysis methodology. The incentives for the conceptual restructuring were: (1) the obvious need to show how the PTS analysis methodology fits into the context of the conceptual model of Structural Integrity at a theoretical level, (2) the need for a transparent workflow structure defining the tasks and data-flow paths during the work, (3) a demand for a clear project organizational structure at the design of other (human, IT) resources at a pragmatic level. This led to the refined evaluation scheme at MTA EK [30] that is introduced on Fig. 7.

The main structure of the scheme was constructed in a way that the definition of the main tasks and the workflow structure of the project are clear, with specific attention given to the key steps of solving the problem at hand. The chart focuses on the 'PTS Structural Mechanics Analyses' aspect, as the processes included in this subject –heat transfer calculations, strength assessments and fracture mechanics calculations– generate solutions of the physical model system that represent the equipment's behavior. Integrity assessment depends on results of preceding calculations. Thermal Hydraulic (TH) assessments create essential boundary conditions for heat transfer and strength calculations, but the initial and boundary conditions of these computations depend on the selection of safety-relevant overcooling sequences. The solutions of the Structural Mechanics problem essentially rely on the ageing stage of the structural materials; the neutron-transport calculations provide the required data for the assessment of the material's state at aged conditions. When evaluating material ageing, the assessment of neutron irradiation assisted ageing is integrated with effects of other ageing mechanisms; this is implicitly assumed on Fig. 7.

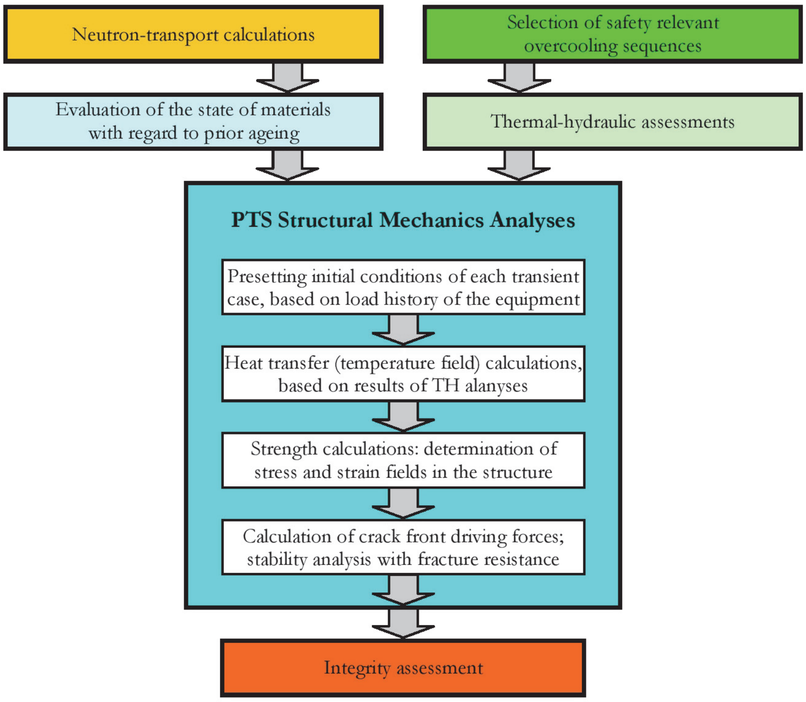

Figure 7: Refined evaluation scheme for PTS Structural Integrity Analyses (MTA EK).

The colors of the different boxes represent the various sub-disciplines working on the subject that are also related to a group of experts. Selecting the safety-relevant overcooling sequences needs special knowledge of the thermal-hydraulic behavior of the energy-generating system, the various safety systems and their possible malfunctions. TH assessments require a deep understanding of the field of fluid thermodynamics, computational TH, etc. Neutron transport calculations demand special knowledge in neutron physics and reactor physics, as well as in their numerical methods, and certain software implementations. The assessments of material ageing need proficiency in material science, experiments, material testing methods, nondestructive methods, etc.. The field of Structural Mechanics Analyses requires expertise in continuum mechanics and thermodynamics of solids; especially thermo-mechanics of continua, fracture mechanics, numerical methods of structural mechanics and their implementations. These facts demonstrate that the PTS evaluation of RPVs is an interdisciplinary task that gathers knowledge from numerous scientific disciplines; it is a typical multi-physics, multi-disciplinary problem.
Proof of the statement that the PTS Structural Integrity Analysis methodology discussed above fits into the general context of Structural Integrity is demonstrated on Fig. 8. Here, the 'Analysis Aspect' face of the 'Structural Integrity tetrahedron' (see Fig. 1) is presented in a special view (after Trampus [98]), and the general structure is supplemented with special information belonging to the PTS Analysis methodology, as it was shown on Fig. 7 earlier. In the terminology of the IT community and of graph transformation systems, this activity is called refinement [21]; namely the evaluation scheme was inserted into the graph-context [87] of the general methodology graph through the interfaces defined by the type graph. The given face of the tetrahedron has three (hyper) edges that meet at the three corner hyper-vertices:

'Loads/environmental conditions', 'Flaws' and 'Material properties'. (Note: the term hyper- will be omitted thereafter, so hyper-nodes will be referred to as nodes; also, the inside nodes of a node will be denoted sub-nodes.) The sub-node 'Loading' of the node 'Loads/environmental conditions' represents data resulting from 'Thermal-hydraulic assessments', while the sub-node 'Env. Cond.' (=environmental conditions) represents the data produced by 'Neutron-transport calculations'. The arrow connecting 'Loading' and 'Env. Cond.' signifies the fact that there is some relation between the two domains, not further specified here (e.g. both of them have influence on the ageing behavior of structural materials).
At the 'Flaws' node, the two sub-nodes represent the size of the flaws and their geometrical distribution both modeled during calculations and also detected in the wall of the equipment respectively. The arrow connecting the two sub-nodes depicts that there exists a relation between the postulated and the detected flaw-size. The nature of the relation is not further discussed here, as the detailed specification is the task of a given project. The outer node labeled 'Qualification of test methods' represents the fact that the qualification of the test method is an essential requirement.
The 'Material properties' node represents material data sets (e.g. thermo-mechanics and strength parameters, fracture mechanics parameters, parameters that describe plastic behavior, etc.) that are necessary for completing Structural Mechanics calculations. The two sub-nodes of the node signify that there are material parameters used during calculations and also derived from material tests respectively. The arrow connecting the two sub-nodes depicts the fact that there exists a relation between the material parameters used during simulations and those evaluated from the tests. The detailed specification of the relation and its discussion is a task of a given, special project. The outer node labeled 'Qualification of test methods' represents the fact that the qualification of the test method is an essential requirement.

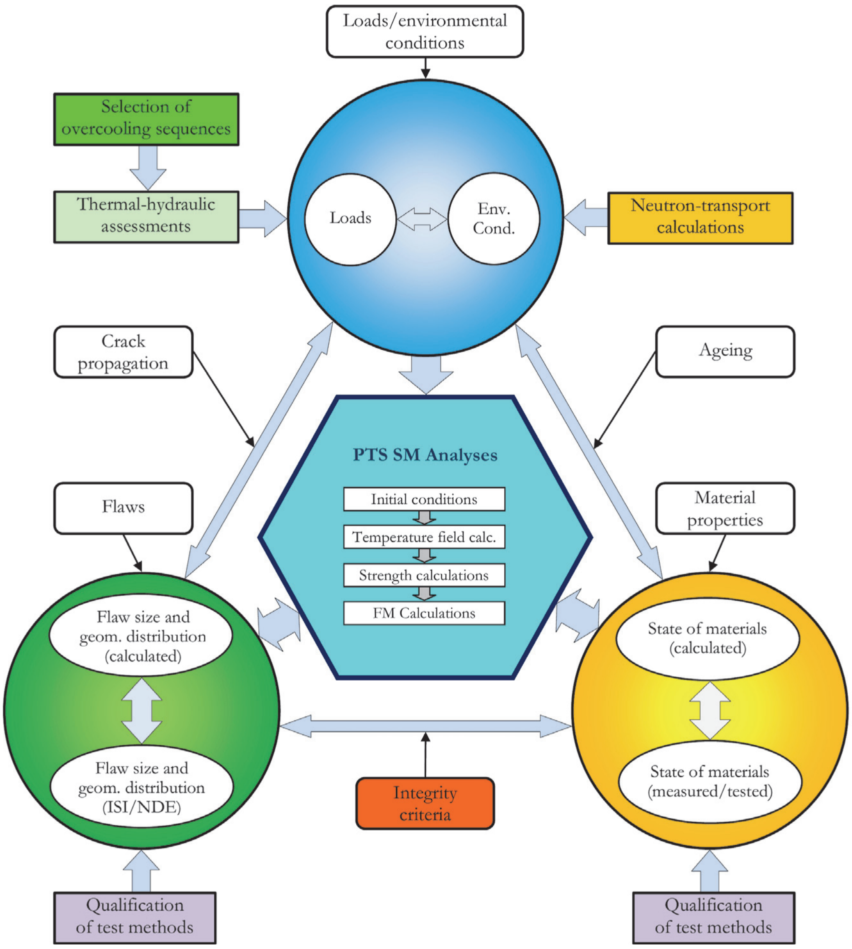

Figure 8: The PTS Structural Mechanics Analyses methodology as the refinement of the Conceptual Model of Structural Integrity.

The edge labeled 'Ageing' represents the aspect that material properties that are valid in aged conditions of the materials must be used in calculations, as they have a large impact on the results; while the edge labeled 'Crack propagation' depicts the aspects that: (1) crack propagation prior to the PTS event needs to be taken into account at the initial conditions of calculations, (2) one of the goals of a given calculation is to elaborate the relations between loads and propagation

behavior of modeled flaws. The edge labeled 'Integrity criteria' expresses the fact that at the final evaluation of the allowable lifetime, a clear relation between critical flaw geometries and the critical material state does exist, that serves as the base of the assessment. Factual, detailed criteria have to be defined for each project.
The key aspect of the refinement was the incorporation of the node labeled 'PTS SM Analyses' (=PTS Structural Mechanics Analyses) into the 'Analysis aspect' of the hyper-graph. This node describes the organization of computational tasks performing the solution of the thermo-mechanics problem that surfaces when evaluating a rapidly cooling, large-scale pressurized RPV. The loadings and material properties serve as input parameters for the analysis, which generates a final output; that is, results describing the behavior of hypothetical or detected flaws during a PTS transient.
The explanation of the graph has been given in the preceding subparagraph, labeled as 'Overview of the Model…'. The high-level model introduced above will be used as a tool in future discussions; namely when deriving the key aspects of the description of various methodologies used in earlier PTS Structural Integrity projects of the RPVs operating in Hungary. The following aspects will be discussed:

- Geometry definition:
    - Parts of the RPV modeled during the study and the geometric model,
        - locations selected for Fracture mechanics analyses;
    - Flaw-size and geometrical distribution at selected locations;
        - relation of postulated flaws vs. detected flaws;
- Description of neutron-transport calculations;
- Materials:
    - Description of materials;
    - Description of constitutive models:
        - thermo-mechanics model and its parameters
          description of ageing;
        - fracture model and its parameters;
          description of ageing;
    - Qualification of material test methods;
- Thermal-hydraulics:
    - Selection of overcooling sequences;
    - Thermal-hydraulic assessments;
- Modeling of physical fields:
    - Kinematical model;
    - Physical fields;
    - Fracture mechanics model;
- Integrity criteria.

CONCLUSIONS

Buildings, structures and systems of large scale and high value are designed for a certain, limited service lifetime, taking the standards and guidelines of the time into account. The standards applied during the design process of a large-scale structure reflect the scientific and technological level of the previous years or decades. However, the standards and guidelines are evolving over time; the goals and requirements may also change during the service time of the equipment. That means that the context of safe operation is part of an advancing world, where the meaning of safety must remain unchanged.
In order to describe the above-mentioned circumstances, the conceptual model of Structural Integrity has been introduced; first in the theoretical context of typed graph-transformation systems that are developed to describe complex systems, initially within the frame of theoretical computer science. It has been proved that the hyper-graph model of Structural Integrity is equivalent to the model given by Lukács.
In the second part of the paper, the system and the RPV of VVER 440-213 was presented, and the notion of PTS was introduced. The general methodology of PTS Structural Integrity Analyses was explained, pointing the key aspects of the calculations out; then the high-level, more abstract description of the methodology was presented. It was demonstrated that the PTS Structural Integrity Analysis methodology fits into the general framework of Structural Integrity. The construction was based on the graph model of Structural Integrity presented earlier. The resulting graph model of PTS

Structural Integrity Calculations gives a concise, illustrative definition of the problem. Moreover, it can be used as a tool for deriving relevant aspects needed for further refinements or discussions.

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