NULIFE – PROJECT CABINET

RPV ASSESSMENT UNDER CONSIDERATION OF CONSTRAINT AND WARM PRE-STRESS EFFECTS

F. Obermeier[1], Tomas Nicak[1], Elisabeth Keim[1], Tamás Fekete[2], Marc Scibetta[3], Tapio Planman[4], Anssi Laukkanen[4], Carlos Cueto-Felgueroso Carcía[5], Iradj Sattari-Far[6]

[1]AREVA NP GmbH, Freyeslebenstr. 1, Erlangen, Germany
[2]Centre for Energy Research, Hungarian Academy of Sciences
[3]Belgian Nuclear Research Centre (SCK-CEN)
[4]VTT Technical Research Centre of Finland
[5]Tecnatom, Spain
[6]Inspecta Technology AB, Sweden

ABSTRACT

At the moment, nuclear power plant regulators do not predominantly consider constraint and biaxial effects in their concepts for failure assessment of nuclear components. The warm pre-stressing (WPS) effect is only partly considered in some assessment procedures and codes. There is also a lack of a harmonized treatment of these effects in the safety assessment of European plants. This paper introduces the project CABINET (Constraint and Biaxial Loading Effects and their Interactions Considering Thermal Transients) which is a collaborative project under the EU's Network of Excellence NULIFE. The overall objective of CABINET is to investigate and understand constraint, biaxial loading and WPS effects in terms of a clearly defined application window, especially in the light of long term operation. The focus lies on already available experimental data and methodologies. The intention is to provide recommendations for a harmonized application of those effects in European nuclear safety assessment. The possibility to include different level of analysis depending on input data and acceptance of National Regulatory Body is also being evaluated. Although the CABINET project is not completed yet, it has been found that it is possible to rationalize the different existing codes.

INTRODUCTION

At the moment, nuclear power plant regulators do not predominantly consider constraint and biaxial effects in their concepts for failure assessment of nuclear components. The warm pre-stressing effect is only partly considered in some assessment procedures and codes. The project CABINET concentrates on the understanding of the constraint and biaxial effects and also on their interaction. Several experiments in the past revealed that shallow flawed specimens or components fail at higher fracture toughness values compared to deeply cracked specimens or components, which is related to the so called loss of constraint. There is also experimental data available indicating the existence of biaxial loading effects which lowers the fracture toughness compared to uniaxial specimens by preventing deformation at the crack tip and forwarding brittle behavior. But there are also other experiments, showing that there is no effect. This situation shall be clarified for the application window of considering those effects. In addition to this it is also convenient to investigate the effect of warm pre-stressing in combination with the effect of crack tip constraint and biaxiality and their interaction. The loading of a flawed structure at a higher – generally at upper-shelf - temperature where plastic deformation occurs, can result in an increase in its subsequent lower-temperature load carrying capacity relative to that expected in the absence of pre-loading. This phenomenon is known as the WPS effect. One can generally speak about the conservative principle of the WPS effect, which means that after a pre-load at high temperature, fracture does not occur if the crack-tip driving force decreases or holds constant while the crack-tip temperature decreases, even if the virgin material fracture toughness is attained. The mechanism of WPS is complex and can be considered as a result of synergistic effects of basic mechanisms, e.g. change of flaw shape, redistribution of stresses and the creation of residual stress zone following plastic deformation around the crack tip. The quantification of the effects, shallow crack, multiaxial loading and WPS and the influencing parameters like temperature, irradiation and flaw shape, with validated experiments and numerical calculations are of prime importance for this project.

This shall be covered by the following work packages:

- WP1: Summary of available data on shallow cracks, biaxial loading and WPS
- WP2: Summary of available predictive methodologies on shallow cracks, biaxial loading and WPS
- WP3: Summary of existing procedures including these effects in safety assessment
- WP4: Definition of the application window in NPP safety assessment
- WP5: Benchmark: Validation of predictive methodologies and application to defined case study
- WP6: Long term operation issues
- WP7: Recommendations for harmonized application in safety assessment considering long term operation issues

A detailed identification of remaining knowledge gaps regarding experimental data and methodologies is also of prime interest.

It is not intended to conduct expensive experiments, but to focus on already available experimental data and analytical tools for the prediction of these effects considering in particular the plant-specific application (application window). The objective is to provide a more accurate assessment of component failure behavior which could be applicable for all kinds of nuclear power plants. This information is expected to enable a more precise and reliable description of failure evolution in components and to be especially valuable considering long-term operation. The final intention is to provide recommendations that allow national and also European regulators to improve the concepts for component failure assessment.

The project CABINET was launched as an in-kind financed project under the EU's Network of Excellence NULIFE (Nuclear Plant Life Prediction) in September 2010 and is supposed to end in March 2013. Because of the rather small project size and short duration, no specific project leader was nominated.

PROJECT STRUCTURE

WP1 Summary of experimental data (VTT)

In part the results of some older test programs have already been re-analyzed in the past, using e.g. the Master Curve methodology and the information from them assessed concurrently to make possible more generic conclusions from the effects of constraint and the loading condition on the fracture behavior. These results, together with more recent data, have greatly improved understanding of the transferability of small specimen test data to real structures, which is in general one aim of this project. In WP1 all literature data which is considered relevant for this project will be collected. Both completed and ongoing test programs and large-scale experiments will be considered as far as results from them are available.

WP2 Summary of predictive methodologies (HAS CER)

The intention of this work package is to provide a concise summary of existing predictive methodologies for analysis of shallow cracks, biaxial loading and warm pre-stress which are applicable for PTS analysis.

WP3 Assessment Procedures & Code Requirements (SCK·CEN)

Harmonization of WPS treatment was already identified in the past as an element that has an important impact on integrity assessment of PWR reactor pressure vessel (RPV). The first step is to identify which nuclear code does explicitly allow taking WPS effect into account. For such code, it is necessary to evaluate under which condition WPS (and eventually constraint) can be taken into account and which procedures apply.

WP4 Application Window (Inspecta)

The definition of an application window for European LWR with respect to safety assessment of components is the prime objective of WP4. By considering the outcome of the data collection activity in WP1, the analysis methodologies in WP2 and the safety assessment rules in different countries, especially in Europe (WP3), the relevant affecting factors and their ranges of application shall be determined for typical cases. The following factors are of interest in this context:

- Relevant materials
- Relevant neutron fluences
- Relevant crack geometries
- Relevant working temperatures
- Relevant loading conditions

Based on this, a generic Application Window for different plant types can be developed.

WP5 Benchmark (AREVA NP GmbH)

The intention of this work package is to define benchmark examples based on the experimental data summarized within work-package one. The methodologies summarized in WP2 will be validated in these benchmark examples. The second step will be to define a case study based on the given code requirements (WP3) and the application window (WP4). The used methods will be compared in terms of results, accuracy, time and effort.

WP6 Long Term Operation (Tecnatom)

The lifetime of nuclear power plants is limited by the ageing of non-replaceable components, in particular the RPV. Main ageing mechanism of the RPV is the neutron irradiation embrittlement, which has detrimental effect on the fracture toughness of RPV materials. Increasing the knowledge on constraint and biaxiality effects in combination with WPS should result in improvements in defect assessment methodologies with can be applied for performing more accurate evaluations of the safety margins against limiting conditions, such as Pressurized Thermal Shock events.

WP7 Recommendations

The final intention of this project is to provide recommendations for a harmonized application of the fracture toughness affecting effects of shallow cracks, biaxial loading and warm pre-stress.

STATUS OF THE PROJECT

This paragraph gives an overview of the work which has been carried out within the first year of the project and highlights the main results which have been achieved during this period.

WP1 Summary of Experimental Data

The approach in WP1 was to collect and preselect the most relevant, well documented previous test data and reviews/analyses of data to be completed with the new test results. The combined data will form the basis to perform the benchmarking, to identify gaps in knowledge and to outline recommendations for the procedure development. This database includes results from several research programs like ORNL HSST (Heavy Section Steel) program [1], Vocalist [2] and CARISMA (**C**rack Initiation and **A**rrest of **I**rradiated **S**teel **M**aterials) [3].

WP2 Summary of predictive methodologies

A summary of the existing models for describing the WPS phenomenon, based on global and local fracture theories respectively was prepared. For the practical applications in PTS assessments, the approximate fracture toughness models according to Wallin [4], Chell & Haigh [5] and Chapuliot [6] seem to be the best available tools at the moment. Application of any of these models in existing PTS calculation methodologies may need case-specific development, which can be implemented through a post-processor module in working systems. The models based on various local approach models for fracture are better suited for modelling WPS test cycles and realistic PTS transients. This is because of the fact that local approach models use information from the direct neighbourhood of a crack tip and other geometry related or time evolution dependent factors can be transformed during calculations, but these models need more R&D and computational resources for a generally accepted industrial use.

WP3 Assessment Procedures & Code Requirements

An overview of relevant nuclear (and non-nuclear) codes was prepared to illustrate the different approaches of WPS and constraint effects. The constraint effect is still not included in most rules and standards. In case of WPS, at least variants of the conservative approach (brittle fracture does not occur for transients which upon attainment of the load path maximum show a stress intensity being monotonic declining versus time) are included in the majority of the standards. An inclusion of the WPS concept into the French RSE-M is in preparation.

WP4 Application Window

The overall aim is to consider the benefits of the WPS effect in structural integrity of nuclear components. The outlined application window is subjected exclusively to the main issues related to reactor pressure vessels of western types. The affecting parameters like loading type, irradiation and crack-tip constraint, and their extensions where limited. The influence of irradiation on WPS is still an open issue. It is expected that the WPS effect decreases with increasing neutron fluence. But some recently published experimental data indicate that there is no influence [7], [8].

WP5 Benchmark

A benchmark example based on a highly irradiated wedge opening load (WOL) specimen tested within the framework of the recently finished project CARISMA (**C**rack Initiation and **A**rrest of **I**rradiated **S**teel **M**aterials) was selected to validate the existing WPS methodologies [3]. This specimen was made from NiCrMo1 UP weld metal (1. generation, lower bound of the weld material) with a fluence of 2,21E19 n/cm^2 (E>1MeV). It was tested under a load-unload-cool-fracture (LUCF) WPS cycle. The specimen demonstrated a significant increase of fracture toughness due to the WPS effect. The approximate fracture toughness models (Wallin, Chell & Haigh, Chapuliot) described in WP2 were used to evaluate this specimen. The comparison of the results shows that all these approaches predict the benefits of the WPS effect very conservatively. In the next step, a case study will be defined, to demonstrate the use of these methodologies in a RPV safety assessment.

WP 6 and WP 7

These work packages are supposed to finalize the project.

Summary

The project CABINET (Constraint and Biaxial Loading Effects and their Interactions Considering Thermal Transients) is introduced in this paper. CABINET is a collaborative project under the EU's Network of Excellence NULIFE. The overall objective of CABINET is to investigate and understand constraint, biaxial loading and WPS effects in terms of a clearly defined application window, especially in the light of long term operation. The focus lies on already available experimental data and methodologies. The intention is to provide recommendations for a harmonized application of those effects in European nuclear safety assessment. CABINET was launched as an in-kind financed project in September 2010 and is supposed to end in March 2013.

Acknowledgement

The authors wish to acknowledge all colleagues from the various organisations involved in this project to lead the project to success as well as the organisations which have provided funding for the project.

References

[1] W. McAfee et al.
Development of a Methodology for the Assessment of Shallow-Flaw Fracture in Nuclear Reactor Pressure Vessels: Generation of Biaxial Shallow-Flaw Fracture Toughness Data
Heavy-Section Steel Technology Program, ORNL/NRC/LTR-97/4

[2] D.P.G. Lidbury et al.
Validation of constraint-based methodology in structural integrity of ferritic steels for nuclear reactor pressure vessels
Fatigue Fracture of Engineering Materials and Structure 29, pp. 829-849, 2006

[3] E. Keim, R. Langer, H. Schnabel, R. Bartsch
Warm Pre-Stress Effect measured at Irradiated RPV Weld Material
Proceedings of the ASME 2005 PVP Division Conference, PVP2005-71196, July 2011, USA

[4] K. Wallin
Master Curve Implementation of the Warm Pre-Stress (WPS) Effect
Engineering Fracture Mechanics, Vol. 70, 2003, 2587-2602

[5] G.G. Chell, J.R. Haigh
The Effect of Warm Prestressing on Proof Tested Pressure Vessels
International Journal of Pressure Vessels and Piping 23, S. 121-132, 1986

[6] S. Chapuliot, J. Izard, D. Moinereau, S. Marie
WPS Criterion Proposition Based on Experimental Data Base Interpretation
Fontevraud 7, Paper Reference A0141, September 2010

[7] G. Chas et al.
Fracture toughness of a highly irradiated pressure vessel steel in warm pre-stress loading conditions (WPS)
Proceedings of the ASME 2011 PVP Division Conference, PVP2011-58029, July 2011, USA

[8] D. Lauerova, V. Pistora, M. Brumovsky, M. Kytka
Warm Pre-Stressing tests for WWER 440 reactor pressure vessel material
Proceedings of the ASME 2009 PVP Division Conference, PVP2009-77287, July 2009, Tschechische Republik