ELEVEN YEARS OF NET NETWORK RESEARCH ACTIVITY - INR CONTRIBUTIONS

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ABSTRACT

The European Network on Neutron Techniques Standardization for Structural Integrity (NeT) was established in 2002, grouping institutions from industry, research and academic media. Coordinated by the European Commission’s Joint Research Centre, the main mission of this network is to develop experimental and numerical techniques and standards for the reliable characterisation of residual stresses in structural welds. Each problem is tackled by creating a dedicated Task Group which manages measurement and modelling round robin studies and undertakes a thorough analysis and interpretation of the results. Over forty institutions are active NeT partners, their specific involvement and contributions being summarised in this paper. The Institute for Nuclear Research Pitesti (INR) is one of NeT founders and its contribution is related to numerical modelling, specimen analysis, material characterisation, data analysis or SANS support. This is also emphasised throughout this paper, together with the specific NeT research topics presentation.

Key words: network, residual stress, structural integrity, diffraction, modelling

Introduction

Over the last two decades, the European Commission has sponsored a significant number of R&D projects under the Euratom Framework Programmes and its Joint Research Centre (JRC) has developed co-operative `European Networks' for mutual benefit on specific topics related to Nuclear Power Plant (NPP) life management [1]. An example of such action is SAFELIFE, focused on establishing European best-practices for deterministic and risk-informed structural integrity assessment of key components, considering all NPP designs, both western and Russian [2]. The SAFELIFE integrated constituent networks were: NeT (*Network on Neutron Techniques Standardization for Structural Integrity*), NESC (*Network for Evaluating Structural Components*), AMES (*Ageing Material European Strategy*), ENIQ (*European Network for Inspection and Qualification*), AMALIA (*Assessment of Nuclear Power Plant Core Internals*), SENUF (*Safety of Eastern European Type Nuclear Facilities*) and APSA (*Network for Incorporating Ageing Effects into PSA Applications*). Further development and integration was due to the FP6 NULIFE Project [3].

The NeT network was established in 2002 (INR Pitesti being one of the founder members), targeting the following main objectives:

- Performance and safety enhancement of European Nuclear Power production by supporting the structural integrity and the safe operation of ageing reactors, and neutron research.
- Promotion of the nuclear energy production safety and neutron research culture within the enlarged EU.
- Development, standardization and harmonization of NDT based on neutron methods with an application to structural integrity throughout the enlarged EU.
- Development of harmonized procedures, accepted by industry and regulators, for reliable evaluation of residual stress, microstructure and defects and procedures for incorporating them in structural integrity assessment.

A sustained research activity was carried up within the NeT framework grouping institutions from industry, engineering, research and academic media. Individual partners' contributions to the work are provided on an in-kind basis. Each problem is tackled by creating a dedicated Task Group (TG) which manages measurement and modelling round robin studies and undertakes a thorough analysis and interpretation of the results. The experimental and numerical techniques applied are briefly outlined in this paper. This paper also contains a synthetic presentation of the current NeT partnership, including the involvement of individual partners. The biggest room is given to the overview of the technical work within NeT, which currently is distributed over six distinct TGs, emphasizing also the INR contribution.

Overview of the NeT consortium

NeT currently has over 40 organizations actively participating. A tabulated overview of the partners and their involvement in NeT is shown in Table 1. The information presented there is an update of that included in [4] according to the subsequent flow of the NeT research program. Most of partners are European based, but also from Australia (1) and Asia (2). One of the particular strengths of this consortium is the diversity of the experimental and numerical methods that can be applied by these partners. For residual stress measurements alone, there are more than five different methods that can be offered by at least one of the partners. Neutron diffraction is mostly used in the round robin exercises, but important contributions to the work have been obtained from the deep hole drilling technique, the contour method and by other stress measurement techniques as well. Next to the stress measurements, there is also a strong materials characterization capacity present within NeT.

On the experimental side one can be mentioned:

- Neutron (ND), X-ray (XRD) and synchrotron X-ray diffraction (HXRD).
- Small angle neutron scattering (SANS).
- Surface (CHD) and deep hole drilling (DHD), contour method (CM) used as strain relaxation based measurement methods.
- Magnetic and ultrasonic (US) methods.
- Metallography, SEM,TEM, EBSD, thermal analysis.
- Monotonic (using both standard and micro-samples) and cyclic stress-strain testing.
- Thermocouples (standard and micro-arrays).
- Strain gauges, digital image correlation (DIC), electronic speckle pattern interferometry (ESPI) and hardness mapping.

On the modelling side, focused on finite element (FE) thermo-mechanical weld residual stress analysis, one can be mentioned the following features:

- 2D, 3D and moving heat source models.
- Material cyclic hardening and annealing.
- Phase transformation effects.
- Use of diverse FE codes (ABAQUS, ANSYS, SYSWELD, Code_Aster).
- Statistical analysis of measured data.

Table 1 *The NeT partners and their contributions*

Organization	Country	Involvement	Contributions
Australian Nuclear Science and Technology Organisation	Australia	TG1, TG4, TG5, TG6	Modelling, ND, material characterization
AREVA NP	France	TG1, TG2, TG4	Modelling, specimen procurement, material characteriz.
British Energy Generation Ltd	UK	TG1, TG4	Modelling, specimen procurement, protocols, data analysis, reports
Belleli Energy srl	Italy	TG2	Specimen procurement, instrumentation
Budapest Neutron Centre	Hungary	TG3	SANS
CEA/Laboratoire Léon Brillouin	France	TG3	SANS
Ecole Nationale Superieure d'Arts et Métiers	France	TG1, TG2, TG3, TG6	Specimen procurement, heat treatment, material characterization, XRD
Complete Technological Service	Czech R.	TG1	Material characterization
Doosan Babcock Energy	UK	TG2, TG4	Specimen procurement, welding, PWHT, final machining, modelling
EC2 Modélisation	France	TG4	Modelling
Electricité de France	France	TG3, TG4, TG6	Specimen procurement, welding, instrumenting, material characterisation, modelling, SANS
Fraunhofer Institut für Zerstörungsfreie Prüfverfahren	Germany	TG2	Magnetic methods
Frazer-Nash Consultancy	UK	TG1, TG5	Modelling
GKSS-Forschungszentrum/ Uni. Kiel	Germany	TG3	SANS
Hahn-Meitner-Institute	Germany	TG1, TG2, TG4, TG5	ND, data analysis
IHI Corporation	Japan	TG4	Modelling
Imperial College London	UK	TG1, TG4, TG6	Modelling, material characterization
INSA-Lyon	France	TG1, TG2, TG4	Modelling, DIC
Institute for Nuclear Research-Pitesti	Romania	TG1, TG2, TG3, TG4, TG6	Modelling, data analysis, material characterization., SANS support
ISIS Rutherford Appleton Laboratory	UK	TG1, TG4	ND
Joint Institute for Nuclear Research	Russia	TG1, TG2, TG3	ND, SANS
Joint Research Centre	EU	TG1, TG2, TG3, TG4, TG5	ND, HXRD, SANS, Protocols
Korea Power Engineering Company	Korea	TG1, TG2	Modelling
National Institute for Materials Physics	Romania	TG3	SANS support
NCSR "Demokritos"	Greece	TG3	SANS
Nuclear Physics Institute	Czech R.	TG1, TG4	ND
Paul Scherrer Institut	Switzerland	TG4	ND
The Open University	UK	TG1, TG2, TG4	Protocols, ND, CM, material characterization
Rolls-Royce Marine	UK	TG5	Specimen procurement
Serco Assurance	UK	TG1, TG4, TG5	Modelling, protocols, specimen procurement, material characteriz.
SVUM a.s.	Czech R.	TG1, TG2, TG4	Material characterization
Technische Universität Berlin	Germany	TG1	XRD
Technická Univerzita v Košiciach	Slovakia	TG1	Material characterization
Technische Un. München, FRM-II	Germany	TG1, TG2, TG4, TG5	ND
University of Bristol	UK	TG1, TG4	DHD, ICHD, ND, UPV
University of Manchester	UK	TG1, TG2, TG4	ND, HXRD, welding technology, modelling
University of Patras	Greece	TG1, TG2	Modelling, protocols
University of South Brittany	France	TG4	Modelling, instrumenting
University of the West of England	UK	TG1, TG2	Modelling, protocols
The Welding Institute	UK	TG4, TG5	Modelling, instrumnenting
Warsaw University of Technology	Poland	TG1, TG2	Material characterization
Yeditepe University	Turkey	TG4	US

Overview of NeT research topics and INR contributions

TG1: Residual stresses in a single bead on plate weld

Task Group 1 was established from the beginning of NeT in 2002. A large amount of contributions have been made to TG1 since then and work in TG1 is almost complete. TG1 studied the residual stresses around a single weld bead deposited on the surface of a Type 316L austenitic stainless steel plate 180x120x17 mm (**Figure 1**). This weld geometry produced a strongly 3-D stress field that was assessed by measurement and numerical round robins conducted in parallel. This apparently simple geometry proved to be very challenging, both for experimentalists and for analysts.

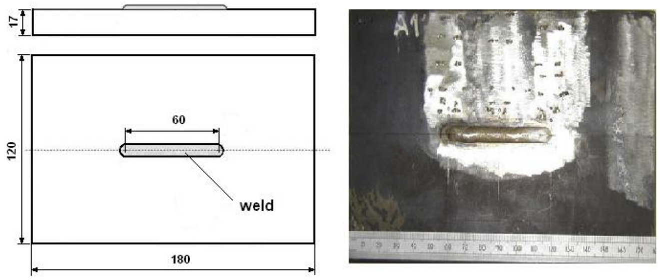


Figure 1 *Schematic of TG1 specimens and picture of specimen A12.*

The numerical round robin was run in two phases: *Phase 1* with unconstrained thermal efficiencies and *Phase 2* using a fixed 75% efficiency and advanced material hardening models. In 2009, a special issue of the International Journal of Pressure Vessels and Piping was dedicated to the experimental and Phase 1 modelling work [5]. The TG1 problem constituted the basis of a weld residual stress simulation benchmark, with target performance measures based on the TG1 results. The benchmark accompanies guidelines for calculating residual stresses in weldments, included in the R6 defect assessment procedure [6].

INR activities and contributions related to NeT-TG1 can be summarised as following:

- Sensitivity studies on the impact on predicted residual stress results of different modelling assumptions like: heat source model, material hardening model, thermal and mechanical boundary conditions aiming to both establish a best practice approach and to aid the overall modelling results analysis [7][8].
- Analysis of thermocouple responses and proposed correction to compensate for the jump down in measured temperatures at some locations observed when the arc was struck. [9]
- Phase 2 residual stress modelling by using both fixed and a moving heat source models (Fig. 2) and an advanced material model (nonlinear kinematic hardening) [9].

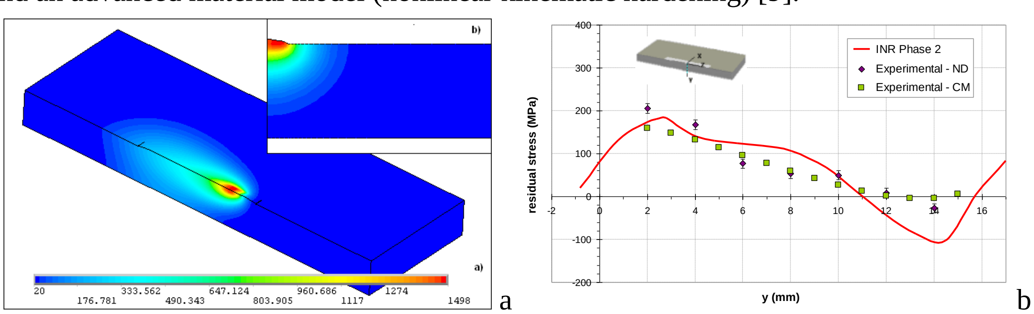


Figure 2 *INR results from TG1-Phase 2 numerical round robin*
a) Computed temperature distribution by using a moving heat source model
b) Computed vs. measured [10][11] transverse RS distribution

The INR modelling work was based on coupled nonlinear thermal and mechanical analysis [12] and the use of the ANSYS Mechanical computer code [13].

TG2: Stress relief heat treatment on welded steel plates

This TG was originally defined in order to assess the effectiveness of post weld heat treatment on an idealized letterbox repair weld [4]. By far the most complex of the NET activities, an 18 bead multi-pass weld (**Figure 3-a**) in a transformable ferritic steel (2.25CrMo) was first fabricated and then stress-relieved at several different temperatures. The nature of the specimen itself presented significant challenges to the measurement of stress. In addition, the sheer amount of computational and human resource required for residual stress modelling, made it clear that a simpler first step was needed [4]. Therefore, a more manageable specimen was proposed (auxiliary specimen) with just three beads laid vertically with an axis of symmetry along the weld line (**Figure 3-b**).

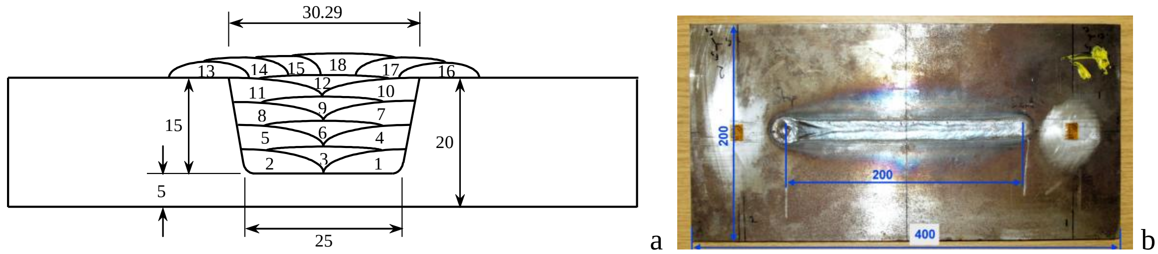


Figure 3 *NeT-TG2 specimens a) Bead deposition scheme for the main specimen b) Auxiliary specimen*

A limited modelling work was carried up to date at INR, namely for the auxiliary specimen, focusing on the improvement of the predictions of a 2-D transverse model by further optimizing the considered mechanical boundary conditions [4][14][15].

TG3: Thermal ageing of duplex stainless steels studied by SANS

TG3 employs SANS to investigate the effects of thermal ageing on cast duplex (austenitic-ferritic) stainless steels, which are used for some components of the primary loop of light water reactors. SANS facilitates the study of material heterogeneities by analyzing the scattering patterns of neutrons after passing through the specimen under investigation. Such analysis can give information about the size, shape and distribution of heterogeneities such as voids and precipitates. The analysed steels are prone to thermal ageing at operating temperatures of around 300°C due to microstructural evolution of the ferritic phase [4].

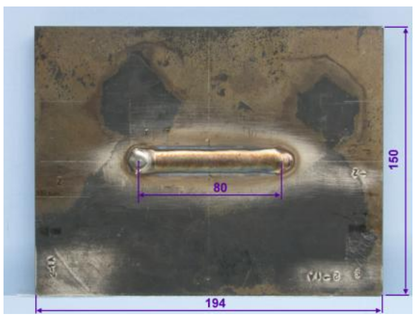
TG4: Residual stresses in a three-pass slot weld specimen in austenitic stainless steel

Task Group 4 was established in 2007 to develop a 3-pass slot weld benchmark considering a Type 316L(N) stainless steel plate 194x150x18mm (Fig. 4). This specimen geometry was considered as being more representative of engineering plant weld repairs than the TG1 bead-on-plate specimen. Measurement and FE simulation round robins are carried out building on the lessons learnt in TG1 and TG2. The role of cyclic hardening in the evolution of residual stress in multi-pass stainless steel welds provides a challenging focus for this task group. The modelling round robin activities are split in two phases, similar to TG1. For the first one, only room temperature monotonic stress-strain data for the base material was available being completed by limited cyclic stress strain-data for types 316L(N) and 316(H) available from other projects. Phase 2 will consider material specific cyclic stress-strain data, at different temperatures, for both parent and weld metal.

One of the three TG4 welded specimens instrumented with thermocouples, namely specimen 2-1A, was further analysed at INR, in order to better assess the real thermocouple junction positions. A special assessment method was setup, basing on quality photographing the specimen together with a set of rulers followed by digital image analysis. The precision of distances and dimensions assessed this way proved to be comparable to that obtained by using microscpe examination [16]. Basing on the analysis results, an improved procedure was proposed for the preparation of two additional specimens instrumented for thermal data aquisition.

The distortion of specimen 2-1A was also measured using the coordinate machine *TESA Micro-Hite* 3D (see an example in **Figure 5**) and quality results were obtained, suitable to constitute a benchmark for welding simulations.

Figure 6 illustrates the INR digital image analysis.



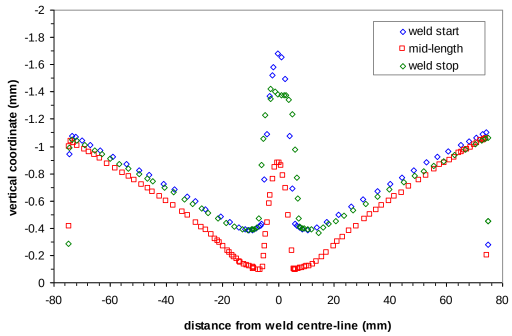


Figure 4 *Photograph of plate 2-1A welded face* **Figure 5** *INR measured distortion of plate 2-1A top face*

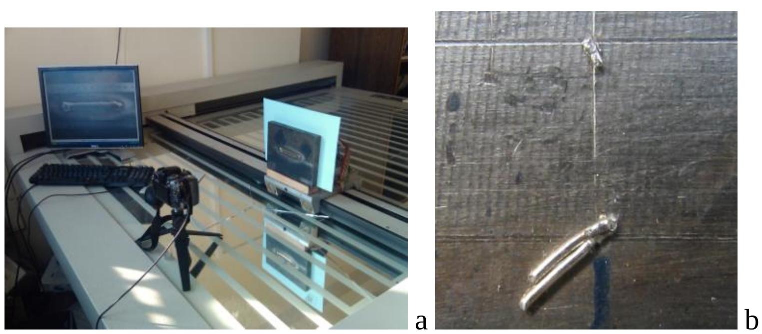


Figure 6 *INR digital image analysis of NET-TG4 specimen 2-1A*
a) Photographing setup b) Detail of thermocouple traces

On the modelling side, for TG4 phase 1 round robin simulations, INR was focused on the development an validation of a simplified procedure for multi-pass welding, having in mind that for real applications, a large number of welding passes may be required. For these cases, full 3D models with moving heat sources are computationally highly expensive and the problem could not be timely solved as required by industry. For instance, a weld repair weld modelling problem involving 18 fill passes and arising from industry practice was included in the currently undertaken FP7 Project STYLE (Structural integrity for lifetime management – non-RPV components) [17] and was attached by INR in this more efficient way, basing also on the TG4 and TG1 exercise. Therefore, a fixed heat source model was adopted by INR for the TG4 thermal analysis (**Figure 7-a**) which proved to ensure well computed thermal cycles and fusion boundaries for all three simulated welding passes. The material model used in the mechanical analysis was an enhanced one, namely the nonlinear kinematic hardening including an isotropic component [18], which ensured relevant residual stress results (see an example in **Figure 7-b**).

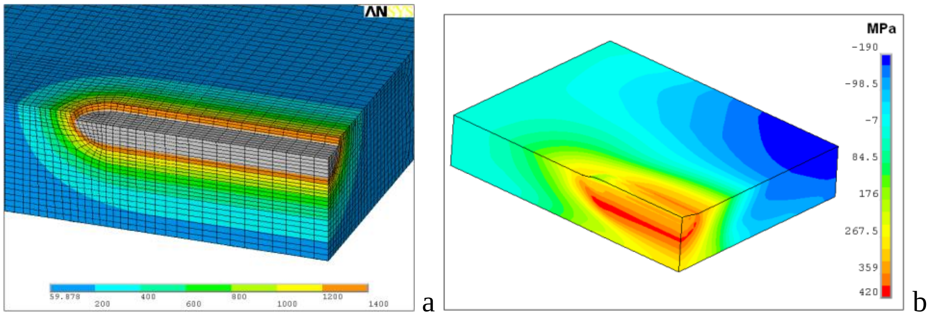


Figure 7 *INR results from TG4-Phase 1 simulation round robin a) Temperature distribution and fusion boundary for 2nd weld run b) Longitudinal residual stress distribution*

TG5: Residual stresses in a ferritic steel autogenous beam edge weld

A ferritic steel (A508) beam 180x50x10 mm with an autogenous weld along one edge (**Figure 8**) is being studied by TG5. This geometry and welding method avoids the addition of any (foreign) material to the system allowing analysts to concentrate on modelling phase transformations in the parent material. Early FE simulation work has shown that phase transformations are sensitive to the welding parameters, so one half of the six test specimens have been welded at a 'slow' speed and the remainder at a 'fast' speed [4].

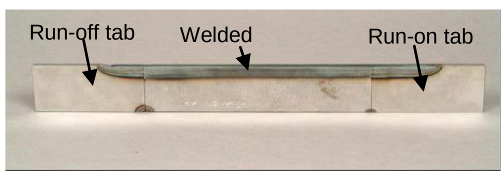


Figure 8 *NeT-TG5 ferritic beam specimen (fast run) with run-on/off plates*

TG6: Residual stresses in a three-pass slot weld specimen in Inconel plate

The problem studied in this newest NeT TG (established in 2012) is similar to TG4 with except the plate thickness (12 mm instead of 18 mm) and the plate material, namely Inconel 600.
INR is being involved in material characterization activities, namely thermal analysis of base metal, in order to determine its specific thermophysical properties (thermal conductivity, specific heat and thermal expansion coefficient) required for the modelling round robin campaign. The later will use also material specific cyclic stress-strain data, similar to TG4 Phase 2. After the completion and launching of the modelling protocol based on experimental data, INR modelling and simulation activities will be carried up.

Conclusions

An overview of the JRC-coordinated NeT network and its sustained research activity was outlined in this paper. NeT investigates mainly welding residual stresses and thermal ageing and precipitate formation in structural materials relevant for nuclear application.

The INR contributions to the NeT research program were also outlined, they mainly consisting in FE modelling, data analysis, material characterisation and SANS support.
The "in-kind contribution" characteristic of the network consortium conducted to longer time-scales but, in counterbalance, this offered the possibility of a thoroughly approach for the studied topics.
The interdisciplinary interaction has stimulated new ideas, novel research studies, improved measurement practice and advances in residual stress prediction methods. Non-European nuclear power users, such as Australia, Korea and Japan, have also significant contributions, expanding the technical base and range of expertise. The network enables the open exchange of relevant results, supporting the principles of the European Research Area.

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