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BIMET: Structural Integrity of Bi-Metallic Components Program Overview

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1 - Introduction

The objective of the project is to contribute to the development and verification of analysis methods which describe the behaviour of an external circumferential defect at the surface of a bi-metallic weld (BMW). The complexity of the problem results from the prevailing mixed-mode loading conditions, the variation in material constitutive equations across the weld zone, and the presence of large residual stress field. Under these circumstances, classic fracture mechanics concepts are difficult to apply.

The project is formed around the performance of two benchmark 4-point bend pipe tests, conducted on a nominal 6" piping assembly, containing a ferritic to stainless steel (A508-308/309SS-304SS) BMW. The weld has been notched at the ferritic steel/buttering layer interface, to simulate plant experiences of the cracking behaviour of such components. A range of analysis methodologies, including conventional flaw assessment methods, J approaches and Local Approach methods will be applied to predict the critical load for initiation of the defect, the extent of crack growth and the path followed by the crack through the weld up to the maximum load. Consideration will also be given to factors such as welding residual stresses, mixed-mode loading, and constraint effects.

The test result will be of direct technological relevance to several of the project partners and the nuclear industry in general.

2 - State of the Art

Bi-metallic welds are a necessity within Pressurised Water Reactor (PWR) and Boiling Water Reactor (BWR) designs where heavy section low alloy steel components are connected to stainless steel primary piping systems. For PWRs, the BMWs of particular interest are those attaching the piping system to the various nozzles of the Reactor Pressure Vessel (RPV), Steam Generators (SG) and Pressuriser.

Recent international surveys on BMW behaviour [1,2] have shown that there are several types of outer surface cracking problems encountered in both PWRs and BWRs which can be essentially grouped into the following two categories

- those related to fabrication and
- those caused by surface corrosion.

At the same time, the occurrence in the literature of cases dealing with analytical and/or experimental aspects of such cracks in BMWs is very rare. The problem of integrity of cracked BMWs remains an important safety issue.

3 - Weld Procurement

To guarantee the quality of the BMW's, a considerable experience and high degree of quality control will be required within the weld manufacturing process.

Five BMW specimens (figure 1) have been manufactured of which two will be tested in 4-point bending, the remaining three being utilised for the experimental determination of welding residual stresses and for the generation of material property data for input to the analysis procedures.

Weld production

The pipe dimension will be of 2500mm length by 22mm wall thickness by 168mm outer diameter. The facility consists of supporting rollers which are compatible with a pipe of outer diameter of 168mm. The inner span is fixed at 700mm although the outer span is variable around 2000mm. The maximum load which can be applied by the facility is 5000 kN.

The welds will be produced according to a nuclear specification. During production, temperature and heat input history will be recorded for latter use in the modelling activities associated with the prediction of the residual stress fields.

Crack propagation will be measured during the experiment by the potential drop monitoring method. This will be calibrated against the post-test crack propagation measurement and also during the pre-test defect insertion operation. A single unique potential drop detection device will be used during the defect insertion and during the test.

Defect design and implantation

An initial design analysis will be undertaken to establish the size of defect required to guarantee propagation during the test and within the loading capacity of the proposed testing facility. This defect will most likely be a partial circumferential defect of depth of the order of half the wall thickness. The defect will be produced by means of electro-discharge machining. It is considered that the precise location of the defect within the weld has been a critical issue and great care has been needed to be applied during the procedure.

Defect measurement

The geometry of the defect was characterised accurately, X-Ray and UT examination has been performed to confirm the initial defect size.

4 - Material characterisation

A key problem that has to be solved for the purposes of the present project is that there exists not only two mechanically different and distinct materials, but also, due to the heat affected zones, a gradient in material properties near to the fusion line [3,4]. For this reason, the analysis work requires extensive materials characterisation across the fusion line, in particular by miniature tensile tests. It is therefore an important result of this task to offer further user guidance with respect to the locations, across the BMW, for which material data have been obtained. The solution of this problem will provide a major step forward for the assessment of heterogeneous structures.

The primary objectiveshas been to characterise the strength, ductility and fracture behaviour of the weld heat affected zones and the dissimilar parent metals. Careful experimentation will provide a basic understanding of the complex welded joint behaviour, essential input for the structural integrity assessments.

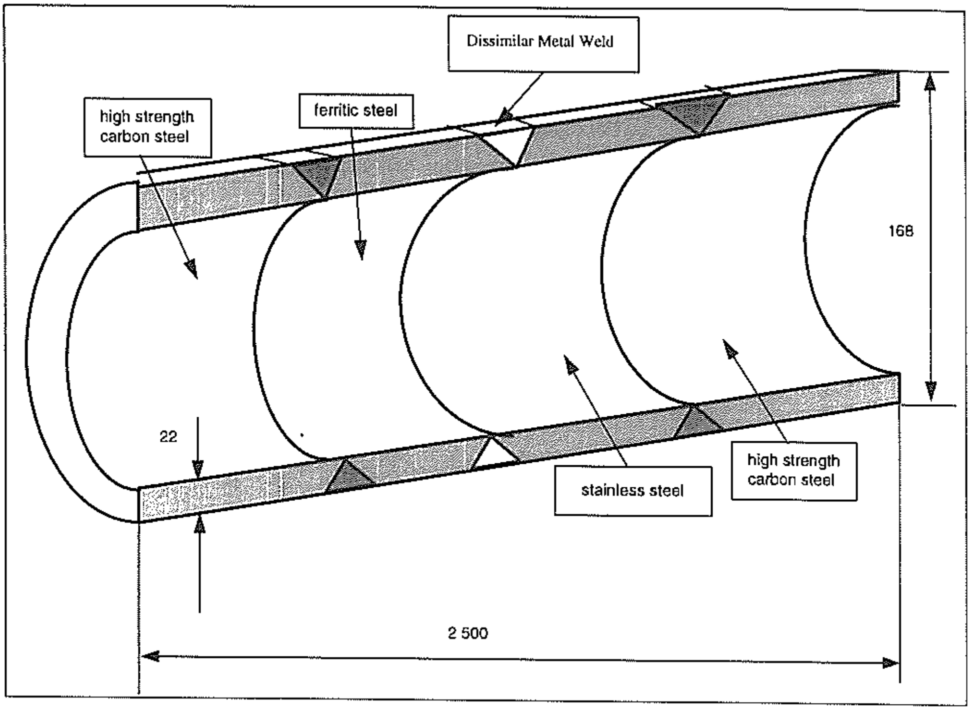

Figure 1 - Weld Assembly Design

Chemical analyses and metallography

The chemical composition of the weldment constituents has been determined.

The metallographic structure of the joint is complex and may vary from weld to weld and even within the same weld. These structures need to be characterised for the damage modelling and also for the mechanical test specimen preparation.

Conventional, miniature and notched tensile testing

Material properties, such as yield strength, elongation and stress-strain curves obtained from tensile tests, are required as inputs for analysis. The gradients of these properties near the fusion line has been measured in the three principal pipe orientations by means of miniature tensile specimens. Stresses and strains has been measured beyond necking by round tensile specimens extracted from the base metals and across the weld metal in a single direction.

Fracture mechanics testing

J_{IC}-values and fracture resistance (R) curves, characterising the crack initiation toughness and ductile crack growth, respectively, are required as inputs to the structural integrity analyses. The size of the welded joint and the need to precisely locate the crack tip, set special requirements for the specimen size and necessitates the use of mainly non-standard fracture mechanics specimens.

The materials characterisation task has required a considerable degree of innovation and the application of the most recent pre-normative testing technologies. Demonstration of a unified testing and analysis approach will offer guidance to the future analyses of similar components.

5 - Residual Stress Characterisation

Bi-metallic welds between ferritic and austenitic steels exhibit a strong residual stress field, both as-welded and after PWHT (post welded heat treatment). Knowledge of the residual stress is an essential input to the structural integrity analysis of the joint, particularly where there is a locally embrittled region near the interface.

The objective will be to determine the residual stress field at the dissimilar weld in the test specimen. The neutron diffraction technique will be applied, and it is intended to establish the capabilities and shortcomings of this technique as applied to the determination of residual stress fields in a medium-sized BMW component.

Modelling

The modelling task involves the evaluation of the residual stress field using a simplified two-dimensional axi-symmetric model which determines the residual stress state of fabrication by simulating the cooling process from the final PWHT.

Neutron diffraction measurements

Neutron diffraction methods will be used to measure the internal residual stresses in the specimen, with particular emphasis on the through-wall distribution adjacent to the ferritic-austenitic interface.

6 - Benchmark Testing

Testing will consist of submitting two cracked tubular BMW specimens to a 4-point bend loading with the objective of obtaining crack initiation and propagation events. The first test has been performed on an EDF facility (figure 2), consisting of a servo-hydraulic actuator, combined with a load cell, and a 4-point bend bench. The test pieces has been EDM notched, without fatigue sharpened. The optimum crack geometry has been evaluated from pre-test design analysis. The first tests has been performed at room temperature, to reduce the extent of the materials testing programme, to a single temperature and to realise a higher level residual stress field and mixed mode loading, at the weld interfaces.

The second test will be performed similarly at room temperature with a smaller crack from 1/2 to 1/3 of the pipe thickness in order to assure larger ductile crack growth before maximum load.

Instrumentation

The specimen instrumentation and the data recording facility has been devised with the two main goals of :

- detecting and categorising the crack ; and
- enabling the best comparison with analytical calculations.

The instrumentation has included the following :

- two clip gauges to measure the crack mouth opening and angle at mid defect position ;
- several potential drop devices, to detect crack initiation and propagation at different points along the crack front ;
- four inclinometers to measure the rotations of the specimens at specified points ; and
- ten strain gauges located near the weldment on both sides of the BMW.

All these measurements has been recorded throughout the test.

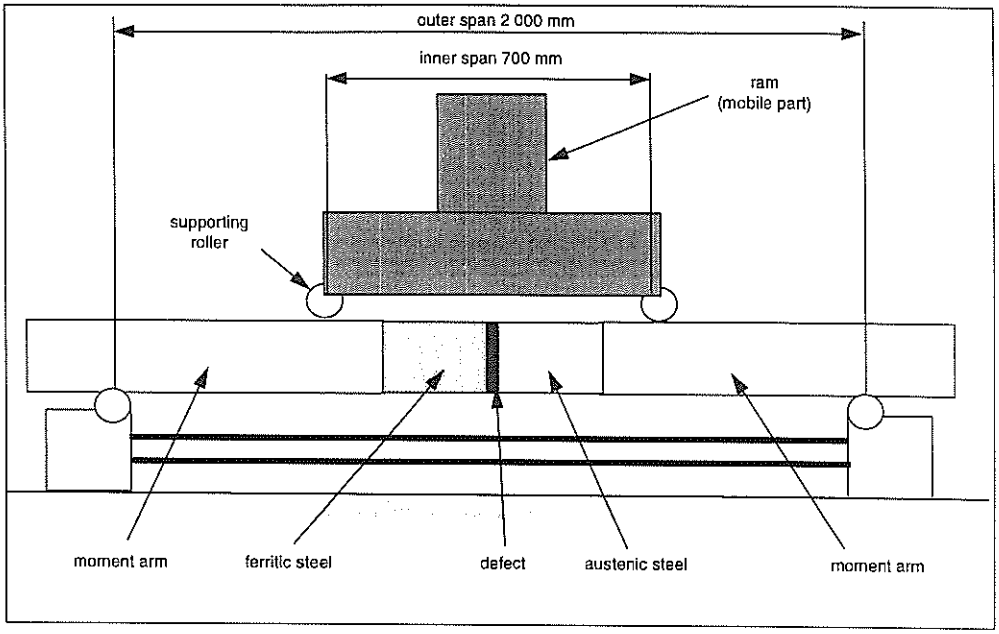

Figure 2 - Pipe Testing Facility

Testing programme

The programme will entail two tests on independent specimens :

- The first test has been done on October 1998,
- The second test will be done on September 1999.

The tests will be conducted under displacement control, to allow propagation beyond the maximum moment.

Post test examination

After testing, the first specimen has been destructively examined to assess the size of the initial crack and the extent of propagation. A maxiximum crack growth of 2.2 mm at the deepest point and 1.2 to 1.4 mm at the surface points has been measured in the buttering. Some fractographic analysis will also be undertaken. A full dimensional check will be made to assess the final shape of each of the specimens (ovality in some sections, curvature).

7 - Analysis

The objectives will be to assess the capabilities of existing analysis techniques for the prediction of the behaviour of a BMW pipe component containing a crack, located parallel to, and at or close to, the fusion line. Three basic methodologies will be examined, conventional flaw assessment methods, more advanced J-methods and Local Approach based methods. The results of these analyses will be benchmarked against the results of the two pipe bend tests. Such an exercise is envisaged to increase the understanding of the role of interaction of two dissimilar (strength mis-matched) materials in structural performance, and to provide input for the further development of models for assessing the structural integrity of bi-metallic welds.

Conventional and Codified Assessment methods

Engineering assessment methods are designed to allow evaluation of cracked structures without necessarily having to conduct detailed finite element calculations. A particularly versatile method is R6 [5] which is based upon the use of a failure assessment diagram (FAD). AEAT will applied the R6 methodology with all these specificities. CEA and EDF will applied specific developments of this methode done in France and included in RSE-M [6]

Engineering Treatment Model (ETM) developed in Germany

The ETM method, developed by GKSS Research Centre, serves for the estimation of the CTOD or the J-integral as driving force parameters.

Due to the normalisation, the equation is a size and geometry independent formulation of the driving force. The ETM handbook is currently in print and will soon be available to the public.

The ETM has recently been extended to strength mis-matched weld cases : ETM-MM.

The mechanical behaviour of the tested cracked dissimilar metal welds will be estimated by means of the ETM-MM method. The result will either confirm the ETM-MM procedure or give rise to modifications to accommodate the special features of the dissimilar joints.

Three dimensional elasto-plastic finite element analysis

In such analyses, the crack driving force is calculated accurately either in terms of the stress intensity factor, the J-integral or the crack tip opening displacement (CTOD). The driving force is then compared with the measured fracture resistance K_{mat}, J_{mat} or δ_{mat}.. From this analysis it is expected that predictions can be made for the initiation of crack growth ; it has to be checked whether predictions concerning the crack path during crack propagation are possible.

Local Approach

Work conducted over the past two decades has demonstrated that assessment methods which reference micro-mechanical failure modes explicitly (often referred to as the "Local Approach") show considerable potential for the prediction of structural behaviour; where the physical mechanism of crack initiation and growth are modelled using constitutive equations derived from basic material properties.

For different models will be checked with experimental results : Damage Models, Cell Models, Beremin Model and Cohesive Zone Model.

Although each model provides adequate formulation for its evaluation, a key problem has to be solved for the purposes of the projects: not only does the fusion line join two mechanically different materials, but due to the heat affected zones, there is also a gradient in material properties near to the fusion line. For this reason, the analysis work requires extensive materials characterisation across the fusion line, in particular by miniature tensile tests. It will therefore be an important result to provide further guidance regarding the locations from where material data should be taken.

The comparison of the results will provide a major step forward for the assessment of heterogeneous structures.

8 - Conclusions

An "Evaluation" task will bring together the results of the different tasks: residual stress determination, materials characterisation, benchmark testing and the findings of the analysis. Its primary role will be a comparison of the results of the analyses and of the benchmark experiment.

Conclusions from these comparisons and evaluations will lead to recommendations on the appropriateness of particular methodologies for the structural integrity assessment of cracked BMW components.

The BMW are needed to connect ferritic components with austenitic piping and are used in safety class 1 systems of all PWR and BWR plants. Their integrity whithout and with hypothetical cracks has to be justified in all condition for the life of the plant; they are also considered in the PWR severe accident studies where it's necesary to define the weakest point of the primary system during these conditions. Due to the complexity of the BMW for fabrication, inspection and analysis, specific programs as BIMET, has to be developped to confirm the quality of the present BMW design rules. This BIMET program is one important step considering tests and analysis of small diameter BMW at room temperature and can support the validation of different engineering methods, as R6 in U.K or RSE-M in France.

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