ABSTRACT

The application of a radiographic inspection procedure in nuclear NDE requires a formal demonstration of the procedure’s capability to detect the supposed defects. The French RSE-M code authorizes different means to achieve the performance demonstration, such as experience feed-back, experiments on mock-ups and computer modeling, which are often employed in combination.

To enable performance demonstration, a new gamma and X-Ray simulation module has been integrated to the CIVA software platform and completes the already available UT and ET modules. This module is based on a combination of NDT radiographic simulation modules developed at the CEA LETI and at EDF R&D. Direct radiation is calculated from an analytical approach (ray tracer and Beer-Lambert law for the attenuation) while the scattered radiation is simulated by Monte-Carlo modeling.

In this context CIVA X-Ray enables simulating a realistic and complex inspection configuration taking into account the most influential parameters of a radiographic inspection. In this paper we illustrate how CIVA-RX addresses the specific requirements of nuclear NDE on radiographic modeling, present examples from three typical application domains, and elaborate on the assessment of an indication’s visibility.

SPECIFIC REQUIREMENTS ON COMPUTER MODELING OF RADIOGRAPHIC INSPECTIONS OF NUCLEAR COMPONENTS

Radiographic inspection as a non-destructive inspection technique is commonly used in numerous application domains, such as aerospace, chemistry, oil/offshore, archeology and nuclear power plants, each of which has specific requirements which must be addressed individually. As opposed to aerospace applications, the components inspected in nuclear applications have two specific properties:

- Rather simple, rotationally-symmetric geometries
- Rather high wall-thicknesses

Rotationally-symmetric geometries

The inspected part’s geometry is one of the key input parameters for a successful simulation. In aerospace applications, where 3-dimensional CAD models of parts are readily available, the capability to import geometry models from legacy CAD systems into modeling solutions is highly desirable. For nuclear applications, however, geometries are commonly described by 3D cross section drawings, which are perfectly appropriate due to the rotationally-symmetric properties of the piping sections to deal with.

CIVA-RX addresses this specific requirement with an integrated extrusion tool, which automatically generates a 3D CAD model suitable for computer simulation from a 2D sketch, which can be drawn by an operator without formal CAD training by simply entering dimensions taken from a 2D plan. Extrusions can be carried out either as translations (for plane parts, often simplified mockups) or rotations around a central axis. Furthermore, the generated 3D model does not resort to facettized approximations of the geometry, but uses an accurate mathematical description of the curved bounding surface, dispatching the operator from the need to specify mesh parameters.
High wall-thickness

The wall thickness range to be dealt with in radiographic simulation determines the mathematical model to be employed. For the rather small wall thicknesses typically encountered in aerospace or chemistry applications, scattered radiation can quite often be neglected, and an analytical straight-line attenuation model is in many cases sufficient to obtain a result with reasonable accuracy. In the intermediate wall thickness range, analytical scatter models handling first order scattering can be useful. For the relatively high wall thicknesses used in nuclear applications, however, scattered radiation must be taken into account in order to obtain a valid result.

The term “scattered radiation” refers to photons reaching the radiographic film after one or more elastic or inelastic shocks with the electrons of an atom, changing their direction and in the case of inelastic (“Compton”) shocks also their energy. Monte Carlo n-particle codes are able to track the path of a photon from the source across the part to the film, taking into account the different interactions in a probabilistic way, and because the history of each photon is traced, provide information about the proportion of scattered radiation with respect to direct radiation (unscattered photons). The radiation build-up factor, defined in terms of “(1+scattered flux/direct flux)” is thus readily available as a result from a Monte Carlo simulation. The Monte Carlo model implemented in CIVA handles Compton- and Rayleigh scattering and photoelectric absorption, which are the dominant interactions in the energy range of 30keV up to about 2MeV. It voluntarily neglects x-ray fluorescence and pair production, limiting the lower and higher energy range limit respectively (In Civa 9 two radiographic modules are available for gamma and X-Ray calculations, pair production is simulated in the X-Ray module).

To illustrate the build-up factor as a function of wall thickness, we provide in figure 2 build-up factors in the wall thickness range of 5 to 60mm for an Ir192 radiography, and in figure 3 in the wall thickness range of 50 to 150mm for a Co60 inspection, obtained by simulation. Figure 4 confronts a radiographic simulation result neglecting scattering (using only the direct radiation result obtained with a straight line attenuation model) with a complete result, integrating scattered radiation. The profile plots illustrate how the build-up factor reduces the image contrast and degrades the indication’s visibility.
Figure 2 - Representation of the Build-up factor in the wall thickness range of 5 to 60mm for an Ir192 source.

Figure 3 - Representation of the Build-up factor in the wall thickness range of 50 to 150mm for an CO60 source
APPLICATIONS

Performance demonstration: Parametric studies

The initial motivation for EDF to get involved in radiographic modeling was inspection procedure qualification, and still constitutes a significant amount of the use of modeling. In a typical performance demonstration, modeling is used to determine the visibility of an indication for all possible variations of the influential parameters. A typical illustration of this approach is the socket weld shown in figure 5 and its representation in CIVA-RX in figure 6. The defects orientation, both lateral and circumferential, are just two of seven identified influential parameters, listed in table 7. For each parameters, a nominal value and a variation range is identified, and by using the batch mode capability of the code, it is possible to carry out the parametric study almost automatically. An equally exhaustive parameter coverage would be expensive and time-consuming if done experimentally.

The simulation results allow the assessment of the importance of each influential parameter on the indications’ visibility, here simply defined in terms of optical density (OD) variation. The values obtained here after correspond to a subtraction of the given optical density on the defect’s image and a simulation launch without defect (ΔOD= OD without defect –OD with defect). Furthermore, an in-depth analysis of each parameter’s impact and a cross-comparison allows to determine the most challenging configurations, for which experiments can be carried out. As such, the use of modeling also allows to better target experimental validations, by using a limited number of well defined configurations to cover the most penalizing configurations, and using modeling to interpolate between these “strategic” radiographs. It is worthwhile to note that computer modeling and experimental validation are not exclusive strategies, but used as complementary tools to demonstrate an inspection procedure’s performance.
Figure 5 - A socket weld and possible crack orientation

Figure 6 - Influence of two parameters on simulated visibility factor

<table>
<thead>
<tr>
<th>Influential parameters</th>
<th>Nominal Value</th>
<th>Variation field</th>
<th>Variation of visibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeve thickness</td>
<td>8.5 mm</td>
<td>6.5 to 10.5 mm</td>
<td>+</td>
</tr>
<tr>
<td>Defect angular position</td>
<td>45°</td>
<td>0 to 90°</td>
<td>+</td>
</tr>
<tr>
<td>Defect orientation</td>
<td>-11.5°</td>
<td>-22.5 to 0°</td>
<td>+++</td>
</tr>
<tr>
<td>Source radial position</td>
<td>0°</td>
<td>-6° to +6°</td>
<td>++</td>
</tr>
<tr>
<td>Source axial position</td>
<td>0 mm</td>
<td>-20 to +20 mm</td>
<td>--</td>
</tr>
<tr>
<td>Fog</td>
<td>0.2 of density</td>
<td>0 to 0.4 of density</td>
<td>o</td>
</tr>
<tr>
<td>Film angular position</td>
<td>22.5°</td>
<td>0 to 45°</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 7 - Influential parameters
Accompanying an in-service inspection: Not fully respected procedures

If computer modeling is sufficiently fast, both in terms of setup and computation, modeling can be put to good use to accompany an in-service inspection. In the following example, we suppose an inspection procedure which was not fully respected, either because of limited accessibility or because of an operator error. In the given example, the source is not aligned with the inspection zone, but slightly displaced.

In order to determine if the radiograph can still be used, the nominal and actual optical density profiles are calculated and compared. Showing negligible impact on the result, the radiography is considered exploitable.

Figure 8 - Not fully respected procedures with a shift of the source positioning

Because of limited accessibility the source had to be positioned at 25mm from the vertical of the defect. We can observe a misalignment of the source with the inspection zone. A comparison is made with the recommended inspection configuration (perfect alignment between source, defect and film).

Figure 9 - Profiles of optical density variation according to the shift of the source

A variation of 0.5% on the optical density is observed in this configuration.
Mockup design

The contribution of computer modeling to better target experiments has already been mentioned. Modeling can also be used to conceive mockups used for experimental performance demonstration: In the given example, an equivalent but easier (and thus cheaper) to fabricate mockup is conceived in terms of a planar test block instead of the actual cylindrically-symmetric geometry. In order to use this simplified test specimen, it is necessary to proof that it is conservative with respect to the original geometry, which means that if an indication is visible on the simplified specimen, visibility on the actual geometry must be equal or better.

The assessment of relative visibility for both configurations is again carried out by computer modeling. We determine the optical density variation for both configurations, and also verify that that the build-up factor in the region of interest around the indication is as high as or higher than in the cylindrical part. We furthermore verify that the image gradient is at least as steep or steeper in the plane mockup. This formal demonstration of conservativeness allows to use the alternative plane test block for the experiment. The plane test block (composed of two blocks) is defined as a multilayer planar specimen composed of two parts of the current material and one part with air inside.

![Figure 10 - Geometry of the real complexes specimens (left), the 2 blocks planar mock-up (right) and their respective optical density profile.](image)

<table>
<thead>
<tr>
<th>Part geometry</th>
<th>Real geometry</th>
<th>Planar mock up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max BU</td>
<td>2.19</td>
<td>2.66</td>
</tr>
<tr>
<td>Min BU</td>
<td>1.60</td>
<td>2.36</td>
</tr>
<tr>
<td>BU on defect</td>
<td>1.95</td>
<td>2.57</td>
</tr>
</tbody>
</table>

Table 11 - BU values on both specimens

From the profiles we observe that the defect is visible with almost the same optical density in the planar mockup, and a smaller extent. Moreover the BU values are higher on the radiographic image of the planar test block compared to the real part geometry. The image gradient on the plane mockup is also steeper than in the actual component.
RADIOGRAPHIC MODELING AND INDICATION VISIBILITY

A recurrent topic in the previous example is the quantitative evaluation of an indication’s visibility with respect to a reference indication. In many cases a reasoning in terms of optical density variations is sufficient, if other characteristic parameters (size, noise, background...) stay the same. However, it is important to keep in mind that an actual radiograph is assessed by a trained inspector, who relies on a global examination to judge the visibility of an indication. A computer screen with its relatively coarse resolution and its limited dynamic range is inappropriate for a visual evaluation; and a computer assisted evaluation of an indication’s visibility is highly desirable, and is the object of current work.

CONCLUSION

CIVA-RX addresses the specific requirements of radiographic modeling for nuclear applications, facilitating the use of rotational extrusions and providing a Monte Carlo computation engine able to take scattered radiation into account. Today radiographic modeling is not only used as a tool to prepare inspections – to demonstrate the performance of a given inspection procedure, using the ability to carry out exhaustive parametric studies, to assess influential parameters and to design mockups – but also alongside an inspection, to determine if deviations from inspection procedures are critical.

One of the difficulties in radiographic modeling is the quantitative assessment of an indication’s visibility. As opposed to other inspection techniques, where quantitative information is readily available, a film radiograph is evaluated by a trained inspector, and since computer hardware is unable to produce a visible result with comparable resolution and dynamic, the visibility of a defect must be determined by alternative procedures. Ongoing and future work is devoted to this issue.

ACKNOWLEDGEMENTS

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REFERENCES


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