Experimental Validation of Build-Up Factor Predictions of Numerical Simulation Codes

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Abstract. The acceptability of results obtained with modeling codes relies on a thorough code validation. Validating scattered radiation calculations in radiographic modeling is particularly difficult, especially for high wall thicknesses. One means to validate results is a cross-code comparison with other modeling codes, and has been carried out for the MODERATO code throughout two international benchmarks. We present here an original experimental approach to complement the validation : As opposed to the traditional experimental setup, using a lead blocker to access the scattered radiation, we propose a strong collimator to separate direct and scattered radiation, applied to wall thicknesses up to 150mm for a Co60 source.

Introduction

Validation of numerical simulation codes is a key requirement for their industrial application, and must define the domain of validity of a code. In general, a validation relies on three types of arguments:

- A theoretical validation, which compares the simulation with analytical results, obtained mathematically on canonical cases. This type of validation is evidently limited to simple configurations, and in radiography might be applied on the thickness of the half-attenuation layer for the primary radiation of a monochromatic source.
- A cross-code comparison, ideally between codes developed by different teams with different techniques, and applied to an analytical benchmark problem (stressing a single phenomenon) or an integral problem (simulating the entire inspection chain).
- Experimental validation, with the obvious drawback that measurement errors limit the precision with which the comparison can be carried out.

Definition of the build-up factor

Scattered radiation is produced throughout the propagation of the primary radiation through the inspection part by elastic (Rayleigh) or inelastic (Compton) collisions of photons with matter. Upon such a collision, the photon's direction is modified, and in the case of inelastic collisions, it transmits part of its energy to the ejected electron. Since the photon's direction after a collision is the result of a statistical process, the scattered radiation generates an additional exposure on the film which reduces the contrast. As the quantity of scattered radiation received on the film must be appreciated with respect to the direct radiation, the notion of a build-up factor is often used. The build-up factor is defined as 1+(scattered radiation / direct radiation). This definition, which originally stems from the



field of radiation shielding, allows to determine the total radiation at a given point from the direct radiation (which can easily be calculated) by multiplication with the build-up factor.

Validation by Cross-code comparison

A first attempt to validate the code has been made in 2008 and 2009 in the frame of an international benchmark, organized by BAM [1]. For this series of numerical experiments, the objective was to simulate the profile of direct and scattered radiation (easily accounted for individually by the participating codes) on steel plates of constant thickness in the range of 10 to 70mm, and up to 150mm for an extension of the initial programme, for monochromatic radiation in the energy range between 100keV and 1MeV. The energies were chosen to bring to evidence differences introduced by the underlying simplifying hypotheses, and are less likely to wipe out differences by averaging over several energies, as would be the case for realistic spectra. The obvious drawback of this approach, however, is the impossibility to compare the simulations with actual experiments, as monochromatic radiation in this range is unavailable.

Experimental validation of the build-up factor: lead blocker

Obtaining experimental values for build-up factors is known to be difficult. In his book "Industrial Radiology" [2], the author R. Helmshaw estimates that is unlikely to obtain a precision better than $\pm 20\%$.

The darkening of a radiographic film is a measure of the total radiation incident on the film, and thus accounts for scattered and direct radiation simultaneously. The experimental determination of a build-up factor therefore requires the isolation of either the direct or the scattered radiation from the total radiation, in order to calculate the build-up.

The traditional setup for build-up factor experiments consists in placing a lead blocker on the part. The objective here is to obtain optical density measurements on the part of the film behind the blocker, and a region of the film outside the zone affected by the blocker. The ratio of both measurements then allows to calculate the build-up factor, supposing that the blocker effectively stopped all direct radiation. This experiment was carried out in our facilities in 2003 in a first experimental validation campaign.

The build-up is calculated from two measurements Od_{total} and OD_s

$$BU_{OD} = 1 + \frac{OD_s}{OD_D} = 1 + \frac{OD_S}{OD_{Total} - OD_S}$$

This experiment is problematic for three reasons:

- It is difficult to obtain within one exposure usable optical density values for both the scattered radiation (underneath the blocker) and the total radiation. If we consider an optical density range of 1.5 to 4.5 usable, the experiment does not allow to obtain build-up values beyond 3, and is therefore limited to small wall thicknesses. A work-around solution would be to carry out two exposures with different exposure times, while aiming to obtain identical or close optical density values in both exposures. Supposing a linear film response, the build-up could then be determined from the exposure times.
- While a sufficiently thick blocker effectively inhibits radiation to pass, its presence

reduces the scattered radiation normally observed without blocker, if its diameter is too large. This effect can easily be demonstrated by simulation (see figure 1), and leads to an underestimation of the build-up.

• Both optical density values also contain the film fog, which must be known and subtracted to calculate the build-up correctly. If two exposures are carried out, it is important to maintain identical development procedures to reproduce the fog.



scattered (left) and direct (center) radiation of the configuration "plate + lead blocker" for a part of 70mm thickness and a 20mm diameter blocker

Experimental validation of the build-up factor: strong collimation

An alternative setup consists in using a strong collimation using drilled plates, in order to isolate direct radiation in the zone underneath the collimation tunnel. A second exposure is then necessary to obtain the total radiation.

Like the previous configuration, this setup is not without problems:

- Two exposures (with and without collimator) are required, with different exposure times. For the build-up calculation, the optical densities obtained must be scaled by taking into account exposure time, supposing a linear film response. An additional complexity is caused by the varying source-film distance with and without blocker, which must also be taken into account in the calculations.
- Like in the previous setup, the separation of direct and scattered radiation is not perfect. A Monte Carlo simulation indicates a small contribution of scattered radiation in the zone of the film under the collimation tunnel. As an example, we obtained a build-up of 1.18 (instead of 1) for a 150mm thick steel part with 150mm collimation behind and 50mm before the part, for a tunnel diameter of 3mm. The spectrum indicates that the scattered radiation is essentially of first order, which means it was most likely generated within the collimation tunnel.
- As far as the fog is concerned, the same precautions as with the blocker setup apply, to reproduce identical and well known fog values.

As stated, the exposure without collimator is carried out with the film situated right behind the part, which introduces a modification of the source-film distance, which must be accounted for in the exposure times to obtain usable optical density values in both exposures. The collimation length is in fact a compromise between the isolation capability for direct radiation, and the increase in exposure time due to the increased source-film distance. If we suppose a linear relation between optical density and exposure time, the calculation of the build-up factor is as follows: With

 t_1 : exposure time with collimation

 t_2 : exposure time without collimation

 BU_r : residue build-up with collimation (not exactly 1)

 $BU\,$: build-up without collimation

I : radiation intensity (constant)

c: a factor integrating geometrical divergence and attenuation (constant for our experiment)

The first exposure with collimation (index 1) provides a measure of the direct radiation

 $t_1.I.c.BU_r = \Delta OD_1$ with $\Delta OD = OD - fog$

The second exposure without collimation accounts for the total radiation

 $t_2.I.c.BU = \Delta OD_2$

We can then calculate the exposure time which would have obtained the same optical density as in the experiment without collimation

$$t_{2} \frac{\Delta OD_{1}}{\Delta OD_{2}} IcBU = \Delta OD_{2} \frac{\Delta OD_{1}}{\Delta OD_{2}} = \Delta OD_{1}$$

With

$$t_2 \frac{\Delta OD_1}{\Delta OD_2} IcBU = t_1 IcBU_r$$

we obtain

$$BU = \frac{t_1}{t_2} \frac{\Delta OD_2}{\Delta OD_1} BU_r$$

or expressed in terms of optical density values read on the film

$$BU = \frac{t_1}{t_2} \frac{OD_2 - fog}{OD_1 - fog} BU_r$$

This result clearly underlines the importance of a precise knowledge of the fog value.

Alternative approach: Distant film

An interesting thought experiment for an alternative experimental setup would be to increase the part-film distance sufficiently to obtain only direct radiation on the film, due to the deviation of the primary radiation upon a scattering event. One might think of this setup as a natural collimation, and the effect is indeed used in micro-focus tomography, where the enlargement factor obtained by increasing the detector distance also comes with the additional benefit of reducing scattered radiation. However, for industrial radiography, this setup is impractical:

- Increasing the source/film distance increases the optical divergence, which must then be compensated for by increasing the exposure time
- When the film is situated right behind the part, it is much less subject to ambient scattered radiation, since it is sufficient to protect the back side of the film by a blocker. If the film is located further away from the part, ambient radiation can reach the film, and additional protective measures become necessary. The experiment must be carried out far from walls, ground or ceiling of the room, and the source must be collimated.

A simulation study to evaluate the feasibility showed that a build-up of 1.18 can be obtained for a distance of 50cm, and 1.12 for 1m. Compared to the value of 1.18 obtained for the collimation tunnel, which appeared simpler to realize, we opted for the strong collimation experiment.

Experimental setup

To carry out the actual experiment, the french Institut de Soudure (institute of welding) developed a mechanical device as shown in the picture. The collimation tunnel is formed by a number of drilled lead plates which can be stacked to increase the tunnel length. The tunnel diameter was 10mm, which is a compromise between separation capability and mechanical feasibility. The mechanical device allows to keep the plates aligned.

The experimental program consisted of a number of exposures with collimations of 10mm before the part and 10, 40 and 100mm behind, to study the effect of the collimation length on the precision. As indicated before, an increase of collimation length requires an increase of exposure time.



Figure 2: Experimental setup

Results

Knowing source-film distance (DSF), exposure times and optical densities, the radio of the build-up values of the experiments with (BU) and without (BUr) collimation can be calculated from the following equation, where index 2 corresponds to the non-collimated experiment.

BUr	<i>t</i> ₂	$* \frac{OD_1 - fog}{OD_1 - fog}$
BU	$\left(\frac{DSF_2}{DSF_1}\right)^2 * t_1$	$OD_2 - fog$

Using this ratio allows to reason in terms of experimental data, knowing that the calculation of the build-up value requires the use of a simulation result, the theoretical build-up for the experiment with collimation BUr:

$$BU_{\exp} = \frac{(BU_r)_{th\acute{e}o}}{\left(\frac{BU_r}{BU}\right)_{\exp}}$$

Reference	Ind	(BUr/BU) _{exp}	BUr _{theo}	BU _{exp}	BU theo	Error Bu (%)
10-70-000	Α	0,826	2,06	2,5	2,4	4
10-70-010	Α	0,776	2,03	2,6		9
10-70-010	В	0,788	2,03	2,6		7
10-70-040	Α	0,646	1,53	2,4		-1
10-70-040	В	0,639	1,53	2,4		0
10-70-100	Α	0,656	1,22	1,9		-23
10-100-000	Α	0,765	2,52	3,3	3	10
10-100-40	Α	0,626	1,74	2,8		-7
10-100-100	Α	0,559	1,28	2,3		-24
10-150-000	Α	0,707	3,34	4,7	4,4	7
10-150-40	Α	0.482	2,12	4,4		0

Comparison of experimental and theoretical (simulated) build-up values

The table shows the following:

- For collimation length "behind" with 40mm, the build-up values are coherent between experiments and simulation for all three plate thicknesses of 70, 100 and 150mm
- For a collimation length of 100mm, an error of 24% is observed between simulation and experiment for the 70mm and 100mm plates (due to exposure time constraints, the 150mm plate could not be characterized at 100mm collimation length)

Conclusions

The correlation of build-up values between experimental and simulation results is globally satisfying, and indicates that the collimation experiment is in principle feasible, although not without problems. The best results are obtained with a 40mm collimation tunnel. On both experiments with 100mm collimation length, differences of up to 24% have been observed. These differences might be due to alignment problems of the source and the stack of collimation plates. Another factor might be the rather important modification of the exposure conditions between both experiments due to the increase of the source-film distance and the necessary exposure time increase.

References

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