Simulation program for reinforced concrete tomography with gamma-rays

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Abstract

The reinforced concrete tomography NDT technique requires detailed and accurate quantitative evaluation of gamma-ray produced images on radiographic film. The new computer program, Gammasim, that simulates such exposures, helps in planning inspections by optimizing source and film placement, filters and exposure times, and is also useful in the interpretation of the results. It is a Monte Carlo-type 3-dimensional program that uses relatively simple but typical rebar and concrete configurations to generate simulated radiographic images and radiographic density profiles. Simple data input and fast novel computer algorithms allow easy and efficient simulations on PCs and laptops. The computational methods are described, and some examples are shown of input screens and typical results.

INTRODUCTION

Gamma-ray radiography applied to the tomography of reinforced concrete structures [1] presents a number of interesting challenges and opportunities for optimizing the results. This type of radiography is somewhat unusual due to the large variety of geometries encountered, the often large thicknesses to be traversed by the radiation and the diversity of features to be observed and measured such as rebar location, orientation, diameters and corrosion, and concrete honeycombing. Since conditions vary widely from one inspection to the next, computer modeling is often desirable to help in optimizing parameters such as the type of gamma-ray source to use, source and film positioning, exposure times, the use of filters, etc. Computer modeling can also be useful as an aid in the interpretation of the results.

EXISTING RADIATION TRANSPORT SIMULATION POGRAMS

Existing general radiation transport finite-element Monte Carlo simulation programs such as MCNPX [2] and MERCURY [3] are in general very large and complex. They are designed mostly for dose calculations after specified absorbers, and are cumbersome and slow for imaging applications. In these programs, the radiation leaving one volume element enters adjacent elements where all the possible physical interactions are statistically applied (hence the term Monte Carlo). The radiation (modified or not) then enters adjacent cells, and so on. The smaller the volume elements are, the more accurate the results will be, but at the cost of large amounts of computing power and time.

Other radiation transport simulation codes, based on ray-tracing techniques such as XRSIM [4], SINBAD [5], and HADES [6] are much faster and in principle more amenable to imaging applications. Recently the HADES code has been extensively studied and improved by M. B. Aufderheide, et. al. [7]. A limitation of these programs is that only absorption along straight lines connecting the source and the detector is considered. Blurring and backgrounds due to degraded scattered radiation are either not taken into account at all or sometimes applied as approximate corrections [8] after the calculation is finished. Generally only scattered radiation originating from materials surrounding the detector such as the detector housing is considered.

This ray tracing approach is inappropriate for our application, since the mass of the rebars that are being imaged is only a small fraction of the concrete mass surrounding them. There is much radiation scattered in the concrete that reaches the film or detector; often more than direct radiation from the source. It is therefore essential to model this scattered radiation in detail. This is certainly done in finite element programs such as MCNPX [2] that are however too slow and cumbersome for this application.

A new approach was clearly needed. We developed such an approach and we wrote a relatively simple program called Gammasim specialized for our particular application. The next section explains the new approach, and then we describe Gammasim and show an example of input parameters and results.

OUR RAY-TRACING MONTE CARLO APPROACH

As compared to other radiations that loose energy and are scattered almost continuously, electromagnetic radiations such as gamma-rays and X-rays have the property of traveling unaffected for relatively long distances through matter before an interaction takes place. We took advantage of this property to develop what we believe to be a novel approach which we call the Ray-Tracing Monte Carlo method. No finite elements are involved. The only volumes considered by the program are those of the actual objects that are part of the physical arrangement being modeled. The granularity characteristic of the finite

element programs is avoided leading to grater precision increased efficiency better statistics and reduced computation time.

During the computation successive gamma-rays are "launched' from random points within the source (in the case of extended sources) and in random directions. In the case of sources with multiple energies, one of these energies is randomly picked, using a frequency distribution that corresponds to the known relative intensity of each energy for the particular radioactive isotope being used. The intersections of this ray with all the material boundaries are then computed.

Next the probability is considered for the gamma ray to interact along its trajectory and a point of interaction is randomly chosen from a frequency distribution that represents the real interaction probabilities corresponding to the total attenuation coefficients appropriate to the gamma ray energy and the materials being traversed. If the interaction point is at or beyond the plane of the film or detector, the pixel corresponding to the intersection of the ray with that plane is incremented by a value proportional to the efficiency of the film or detector for the energy of the arriving radiation.

The total mass attenuation coefficients are obtained from the XCOM data base [9] maintained by the National Institute of Standards and Technology (NIST). The types of interactions that occur at the energies of interest to us are the photoelectric effect followed by the possible emission of a fluorescence X-ray, the Compton effect followed by a scattered and degraded gamma-ray emitted with an angular probability distribution given by the Klein-Nishina formula, and elastic scattering followed by a gamma ray of the same energy but propagating in a different direction. The remaining interaction, namely pair production with subsequent annihilation radiation only occurs at higher gamma ray energies and has not yet been considered but can be easily included in the future. At the interaction point, one of these processes is chosen at random with probabilities that are in accordance with the partial mass attenuation coefficients also tabulated in reference 9. If degraded or scattered radiation results, a new ray is generated by picking the direction from the appropriate random distribution, and the process is iterated until either the radiation is totally absorbed or the ray crosses the detector or film plane in which case the corresponding pixel is appropriately incremented as mentioned above.

After launching a large number of simulated gamma rays, the above procedure leads to a two-dimensional pixel density distribution that mimics the results one would obtain on radiographic film. One can then calculate projections, evaluate backgrounds and rerun the program after making changes to improve the configuration or to establish the feasibility of a certain inspection before spending time and effort on actual measurements.

Even tough our approach is very efficient since it doesn't need to propagate radiation in small steps, there are occasions in which the concrete preceding the rebars to be studied is so thick that much time is spent in following a large number of gamma-rays from the source that are absorbed before reaching the volume of interest. To solve this problem we developed a computational technique used when the volume preceding the rebars, present cylindrical symmetry around the line perpendicular to the film that passes trough the source. Gamma rays are launched as usual and the small fraction of gamma or X-rays that make it to a plane just preceding the rebars are then reused or "cloned" by rotating them in small steps (e.g. a thousand times) around the symmetry axis, thus saving most of the computation time spent in reaching the rebars. This trick has allowed us to calculate cases that otherwise would have been unreasonable to tackle.

THE GAMMASIM PROGRAM

We implemented the ideas outlined in the previous section in a program called Gammasim that is specialized in simulating simplified versions of some of the most common geometries encountered in the tomography of reinforced concrete structures. We consider in this program infinitely long and parallel cylindrical rebars and voids embedded either in an infinite concrete slab or close to the edge of a semi-infinite slab or in an infinite column or beam with surfaces parallel to the rebars. The reasons we adopt these simplifications are to reduce running times on a PC and to keep the parameter input as simple and fast as possible A more complete and more complicated program may be written in the future, but for now we are able to obtain the answers we need by using the present version.

Figure 1 shows the screen used for entering the data that define a problem, and figure 2 indicates the geometry of the simulation defined by the data shown in figure 1. This diagram is generated by the program, but here we added labels to indicate the system of coordinates used, and the positions of the gamma-ray source, the rebars, the filter and the film. The gray area in figure 2 represents the concrete, and we see that in this case the source has been placed in a cylindrical orifice drilled in the concrete.

We see in figure 1 that Ir 192 has been selected as the gamma-ray source. The program also contains the required information for Cs 137 and for Co 60 which can be selected by using the drop-down list. The source diameter in mm and the diameter of the drilled orifice where the source is placed are then entered. For external sources a gamma-ray collimation angle can be entered, and this entry can be automated to correspond to the solid angle defined by the source and the film. In the present example of an internal source, this entry doesn't apply.

**Fig. 1   Example of an input screen defining the parameters of a Gammasim
simulation (see text). The geometry defined by this screen is shown in Fig. 2**

The X and Y concrete boundaries are entered in the four boxes labeled "Concrete". In
the present example we are modeling an infinite slab and we therefore entered only Y-
values. The boundaries of up to four filters can be entered, and the materials are selected
from drop-down lists containing eight common metals. Here we have selected a 1 mm
thick lead filter. The film position is entered in the box labeled "Film Y". The positions
and diameters of up to seven rebars labeled "Iron 1" through "Iron 7" can be specified as
well as the positions and diameters of two cylindrical holes labeled "Void 1" and 2.

The "Gated Spectrum" X and Z inputs allow the possibility of defining an area on the
film for which the program computes the energy spectrum of the radiation reaching the
film. This is often of interest to evaluate in detail the contribution of scattered radiation to
the film exposure and to make judgments on what filters to use to minimize it. In this
case we have not defined this area and the program will then integrate over the entire
film. The "Profile" Z inputs define a band on the film over which the simulated optical
densities will be integrated to generate the type of exposure profiles shown in figure 3.
The program also always generates a profile integrated over the entire width of the film.
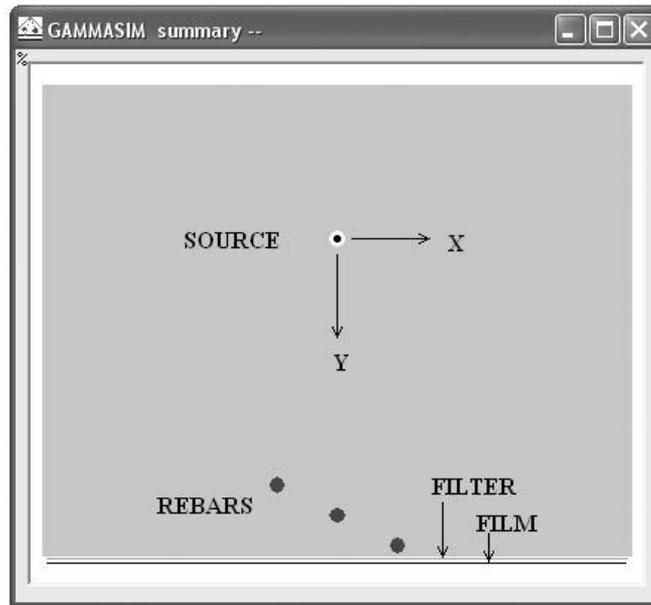
Fig. 2 Geometry of the simulation defined by the input screen shown in Fig.1. The gray area represents the concrete volume. The labels have been added to indicate the items relevant for the calculation and to show the coordinate system used. The Z-axis is parallel to the rebars.

The "Cloning" on-off selection refers to the computational "trick" mentioned in the previous section which was used here. The "Multiplier" value specifies how many times each of the gamma rays launched from the source is to be reused by the program and the number of gammas launched is specified in the "# gammas" box. Finally, a running count of the gamma-rays launched is shown during program execution, as well as elapsed time.

The program contains extensive input error checking with warning messages, and will not start unless consistent parameters have been selected. At the end of each run the results are written to an Excel spread sheet that automatically generates a number of tables and charts.
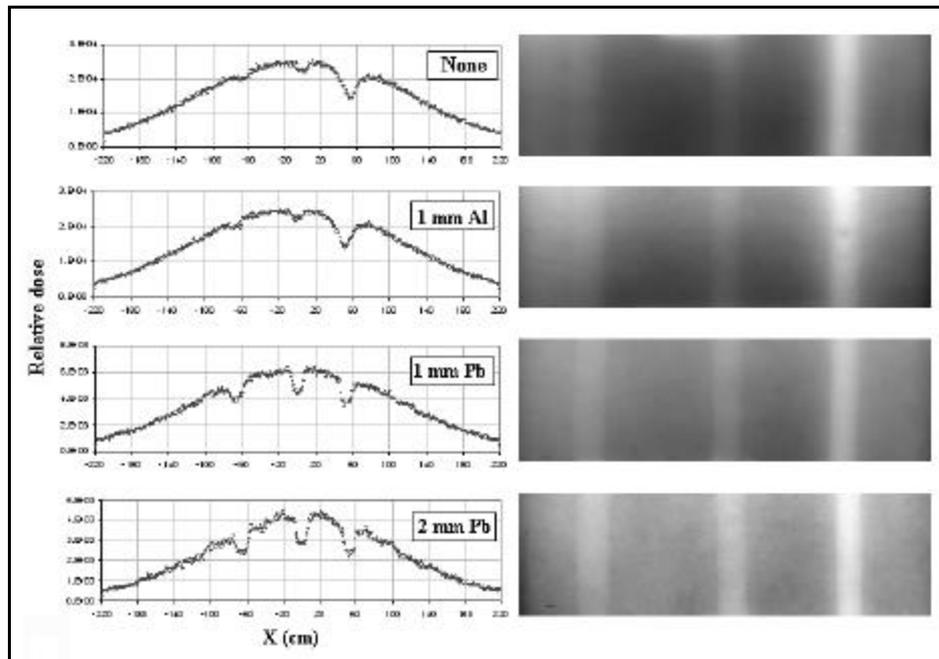
Fig. 3 Profiles obtained with Gammasim with different filters (left) compared to experimental results (right). The curve shown for the 1 mm lead filter was obtained with the input parameters shown in Fig. 1

RESULTS AND CONCLUSIONS

Examples of results obtained with Gammasim during a study to optimize filters are shown in figure 3. Comparison between Gammasim dose profiles and the corresponding radiographic images at the right show very good qualitative agreement. Preliminary calibrations of the film showed the sensitivity to be approximately constant over the energy range measured. More extensive calibrations will be necessary before detailed quantitative profile comparison can be made. We see both in the data and in the corresponding simulation that, without filter, the image of the leftmost rebar is almost totally obscured by scattered radiation. We see both in the simulation and in reality that the 1 mm lead filter achieves a very considerable improvement. The geometry used for these tests is the one shown in figure 2 and the parameters used for the 1mm filter simulation are the ones indicated in figure 1.

The computation time for the 1 mm absorber case was of 52 minutes on a PC with a 1.8 GHz clock rate. On the same machine an equivalent computation without cloning would have taken an estimated 500 hours because of the extremely low transmission for the thickness of concrete traversed. Only about 0.01 % of the gamma rays that leave the source reach the film, and of those, even with the filter in place, only about 50% are coming directly from the source

In conclusion our Ray-Tracing Monte Carlo approach has already been very useful in a simple application used in simulations for reinforced concrete tomography. The physical processes involved in the scattering and absorption of the gamma-rays are modeled in detail without the unavoidable granularity and slowness of finite element programs. With further refinements and improved detector calibrations, simulations based on this approach have the potential of becoming at the same time very accurate and very efficient.

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