Compton back scatter imaging for mild steel rebar detection and depth characterization embedded in concrete

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ARTICLE INFO
Article history:
Received 4 July 2014
Received in revised form 21 October 2014
Accepted 28 October 2014

Keywords:
Compton scattering
Steel rebars
Concrete
Gamma ray
HPGe detector

ABSTRACT
A novel non-destructive Compton scattering technique is described to ensure the feasibility, reliability and applicability of detecting the reinforcing steel bar in concrete. The indigenously developed prototype system presented in this paper is capable of detecting the reinforcement of varied diameters embedded in the concrete and as well as up to 60 mm depth, with the aid of Caesium-137(137Cs) radioactive source and a high resolution HPGe detector. The technique could also detect the inhomogeneities present in the test specimen by interpreting the material density variation caused due to the count rate. The experimental results are correlated using established techniques such as radiography and rebar locators. The results obtained from its application to locate the rebars are quite promising and also been successfully used for reinforcement mapping. This method can be applied, especially when the intrusion is located underneath the cover of the concrete or considerably at larger depths and where two sided access is restricted.

1. Introduction
Non destructive testing and evaluation is an indispensable tool being widely used for pre and in-service inspection including remnant life assessment. From the 5 conventional methods in the 1950s, we have a host of advanced NDE methods today. Ionizing radiation based methods such as radiography is widely used for detection of volumetric defects such as voids and porosities in welds and castings. In the field of condition management, radiography has been used for defect and corrosion detection in bridges etc. A major disadvantage of radiography is the need for access from both sides. Compton backscattering of X-ray or gamma ray photons is an advanced NDE technique based on the detection of the scattered radiation. In this technique, a collimated beam of X- or gamma ray photons interacts with the material and the scattered radiation from a relatively small voxel volume is detected using point by point or line by line or plane by plane scanning [1]. This scattering basically depends on the electron density of the scatterer and hence its mass density [2–4]. The information obtained by this technique strongly relates to the material density from point to point [5,6] thus making it possible to map variations in with good sensitivity. The main advantage of Compton backscatter imaging is that it is non-invasive, non-contact and requires only single sided access. This aspect of single sided access makes it an attractive technique and has been explored for a variety of applications.

One of the important parameters in assessment of aging structures is the detection of rebar including rebar corrosion. While a number of NDE techniques such as ground penetrating radar [7], electromagnetic [8], thermographic [9], eddy current [10], ultrasound [11], impact echo [12], radioactive and acoustic emission [13] have evolved and are being applied, each have their own advantages and limitations. Evaluation of steel rods in reinforced concrete or rebars through Compton backscatter imaging has been attempted in a limited way internationally. Esam et al. [14] described the methodology for optimization of the Compton scattering technique and presented the results that illustrate the capabilities of the method to locate 21 mm steel rebar at a depth of 18 mm in concrete. Shiro Tuzi et al. [15,16] carried out their experiments using Cobalt-57 and Barium-133 gamma source and Sodium Iodide detector for the study of characteristics of rebars in concrete structures. Boldo et al. [17] used Americum-241 radioactive source and high resolution CdTe semiconductor detector to detect the steel reinforcement bars positioned at a depth of 20 mm from the concrete surface. Nares Chankow et al. [18] had demonstrated the Differential Gamma-ray Scattering Technique (DGST) to differentiate the steel rebars in the concrete mortar.

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http://dx.doi.org/10.1016/j.nimb.2014.10.029
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The maximum depth at which these bars were located in all these cases was about 25 mm only. In thick walled structures such as the reactor containment or biological shield in nuclear facilities, the rods are likely to be embedded still deeper. At the authors lab, an innovative dual purpose system has been indigenously designed which can be used for Compton back scatter imaging as well as for transmission and emission tomography. This paper focuses on the feasibility of detection of steel rods/rebars at depths greater than 25 mm in concrete. The experimental results are validated through a well established NDE method such as radiography. The successful detection opens up a plethora of practical application possibilities of this unique and seldom used back scatter imaging technique. A brief theoretical background of the physical principle is given before elucidating the experimental part.

2. Physical basis of Compton backscatter imaging

X-rays and gamma rays interact with matter primarily by photo electric effect, Compton scattering and pair production. In Compton scattering which is most predominant in the energy range from 150 keV to 3 MeV, gamma rays interact with matter and transfer its energy to the electrons in an atom. The photon energy shift is due to the incoherent scattering of photons with virtually free atomic electrons [19] (a process called the Compton effect) whose electron binding energies are much less than the energy transferred and the photons with reduced energy scatters at some angle to the original direction of travel [20]. The gamma scattering technique is so significant because the photon energy have a single-valued relationship to the scattering angle after single scattering event. The Compton’s energy loss equation [21] relating the secondary photon energy, the scattered intensity (I) is directly proportional to the physical density ($\rho$) of the material to be investigated. Scattering enables simultaneous collection of voxel-by-voxel information along the path of the incident radiation. The larger the difference between densities of the heterogeneous materials, the greater is the difference of detected intensities from scattering. Thus, by scanning the position of the scatter voxel, a density map of the materials can be ascertained.

3. Experimental design and measurements

An indigenously designed and developed system is used in the present experimental work. The system basically consists of an isotopic gamma ray source, an object platform and a detector system. A $^{137}$Cs radioactive source of activity 4.2Ci (155.4 GBq) is selected for the present work. This isotope is preferred because of its monochromatic nature of 662 keV photons. A coaxial high purity germanium (HPGe) detector with an energy resolution of 1.93 keV (FWHM) at 1.33 MeV ($^{60}$Co energy), relative efficiency of 45.8% (at 1.33 MeV) and a Peak-to-Compton ratio of 68:1 is used for detection of the scattered photons. The source and the detector are housed in a lead enclosure and mounted separately on an automated PC/CNC controlled six axes system. The source and the detector system can be moved tangentially and vertically with the positional accuracy of ±50 microns. A source to test object distance is 77 cm and object to detector distance is 42 cm respectively, with a scattering angle of 108° and is maintained throughout during the course of the experiments. The objects investigated are rectangular Concrete Masonry Unit (CMU) of dimensions of 150 mm × 100 mm × 100 mm prepared with a composition of 20% ordinary Portland cement, 40% sand, 40% aggregate(fine gravel and crushed lime stone) and an

Fig. 1. Compton scatter geometry.
appropriate amount of water. Fe250 graded mild TMT rebar of
diameters 12 mm, 20 mm and 30 mm (IS 456:2000 standards)
are inserted during the preparation of the concrete block. The rods
are positioned longitudinally at varying spatial distances and at
different depths from the front end of the concrete. The specimen
is positioned manually on the four axes system and a computer
controlled servo motors are used to move the specimen past the
collimated source and detector. The four axes system could be dis-
placed with a minimum displacement of ±10 μm in three perpen-
dicular directions and ±0.25° for rotary stage. The pulses from the
detector are amplified using spectroscopic amplifier and processed
through 8K channel pulse height analyzer. The four axes position-
ning control as well as the data acquisition and analysis are com-
pletely automated through software, developed for this study.
The crucial system parameter of the back scatter studies is the
’voxel or sensitive volume’, which basically depends on the source
and the detector collimation and their geometry. In this case, the
voxel is attained by collimating the source and the detector using
5 mm diameter lead collimator generating a voxel of 14 mm extent
along the direction of probing. The detection of photons originating
outside the voxel volume as a result of multiple scattering is con-
trolled using a soft collimation within a specified energy interval
[24]. Spectrum of each voxel is recorded by moving the test spec-
mimen laterally and vertically across the source and the detector col-
limators, in steps of equal increments. The other way of scanning
the specimen is by translating the radioactive source and the detector as a combined assembly as required in the field applica-
tions. The 244 keV scattered photons are recorded in the HPGe
detector for 1Ks to achieve high count rate and for attaining high
precision. The set of experiments conducted aims at the detection
of the rebars, its orientation and estimating the spatial resolution
of the reinforced inclusions embedded in the concrete.

Radiography of the concrete samples is carried out using a Bal-
teu 225 kV X-ray machine with a focal spot of 0.8 mm × 0.8 mm.
Single wall single image technique is used. To minimize unsharp-
ness, a source to focal distance (SFD) of 800 mm is used. The radiog-
ographic parameters for imaging the concrete samples are listed
in Table 1. Sensitivity achieved in the radiographic images is 2–2T and optical density in region of interest is in the range of
2.0–2.5. These radiographs were digitized using Film Digitizer
(Model Array 2905HD) with a resolution of 50 microns. Appropri-
ate pre-image processing techniques are adopted to enhance the
image for accurate dimensional measurements.

The real time visualization along with automatic data collection
to locate rebars is performed by a rebar locator. It works with the
eddy current principle with pulse induction as the measuring
method. This meter is used to estimate the bar size with the prior
knowledge of the cover depth of the concrete and vice versa. When
the hand-held search unit is moved along the concrete surface, a
beep sound indicates the existence of the rebar and the rebar size
is exhibited in the display unit of the rebar locator instrument.
Rebar detectors are used on our experimental concrete specimens
for the practical judgments of the inclusions as drawn from our
method.

4. Results and discussion

The inclusions and the anomalies within a sample can be exam-
ined by investigating the intensity of the scattered radiation by
performing a scan of region of interest. The scattering is carried
out by sweeping past the 150 mm concrete brick across the
source–detector collimators and the scattered photons are col-
lected using an energy window as dictated by the combination of
the spatial resolution desired and the energy resolution of the
detector.

The first set of experiments is performed with the inclusions
like steel rebar and a void in the concrete and this is organized
to test out the feasibility and reliability of the prototype instru-
ment for the detection of the defects in the specimen. Fig. 2 shows
the scattered intensity profile at a depth of 20 mm from the surface
of the sample. As the scanning progresses, from the left to the right
as seen in the graph, there exists a variation in the gross counts
from one extreme to the other extreme of the test object. The rea-
son is, as the radiation perceives the steel rebar, the scattered
counts reaching the detector attains a maximum value due to the
sudden increase in the electron density of the material (den-
sity = 7.9 gm/cc) as seen by the sensitive volume (as per Eq. (3)),
whereas the counts reduces to a minimum due to the reduction
in the electron density of the void indicating the confirmation of
the existence of the void. The pattern followed in the formation
of the crest and the trough signifies the existence of the steel rod
and void inclusions in the sample and the local maxima and min-
ima disclose the exact location of the integrated material. The fall
of counts in the in-between points is mainly because of the scatter-
ing volume intermingles either between the concrete and the steel
rebar or with concrete and void. The least count at the extremes
are contributed to the reason of scattering volume partly lying in
the concrete and as well as in air. The very same reinforced con-
crete sample is radiographed using 180 kV X-ray machine. The dig-
itized radiographs with a resolution of 50 μm are processed for the
detection of voids and steel rebar in the concrete. The inclusions
revealed by the radiography technique matches very well with
those obtained by our non destructive testing system demonstrat-
ing that our system can be used for the detection of anomalies
underneath the cover of the concrete.

The specimen with the same layout as mentioned elsewhere
with a pair of rods is translated step wise across the source–detect-
ror collimators to acquire the line scan data. Fig. 3a shows clearly
the existence of two steel rods at the location of 40 and 110 mm
along the abscissa with a good spatial resolution. The experiment
is further resumed by increasing the counting time 1000 s more to witness the presence of the inclusions (Fig. 3b). It is observed that the contour followed for this case reflects the same features as in the Fig. 3a, but the intensity of the scattered component has been increased by 45%. The line profile from the radiographic image as shown in Fig. 4 indicates the distance of separation of rebars as 708 mm, which coincides with the measurements made by our method with a marginal error of only 1.1%. This analysis reveals that our system can be used for the assured detection of the steel reinforcement in the concrete.

For the successive detection of rebars of different diameters as shown in Fig. 5, the sample is scanned across the direction of the incident source beam. The back scattered signal of the sample with three rods of diameter 12, 20 and 30 mm located at a depth of 10 mm is collected for a specified time interval in equal pace by focusing the source and detector collimators for each voxel in the region of interest. The pulse height spectrum is obtained and the scattered counts registered at the region of interest are plotted against the scanning distance as shown in Fig. 6. Analysis of the graph depicts the existence of the reinforcement at the proper location as conferred by the radiographic images (Fig. 7). The confirmation of the signature of the inclusions in the figures proves the position sensitive capability of the Compton scattering to distinguish between the rods of various diameters embedded in the concrete.

A series of scanning is also carried out at different depths (20–60 mm) to explore the potential of the experimental set up present in our laboratory. The counts profile of the scattered spectrum at different depths for a single rod is divulged against the stepping motion in Fig. 8. It is found from the graph, the presence of intrusions are prominently seen up to a depth of 40 mm at the scanning position of 60 mm in the less dense matrix. As the scanning progresses to a deeper depth, the incident and scattered photons attenuates to a larger degree, the counts registered at the detector falls rapidly and hence the resolution of detection of rebars
Rebar of scattered intensity signal and the basis behind it, is due to the trend followed with respect to the previous case is the reduction with 30 mm rod in the same layout. The only difference in the evidence is furthermore extended to promote the established fact material (rebar) implanted in the concrete. The experimental evidence saturated counts designate the upright position of the high dense material (concrete) focused by the voxel volume and the region of the target co-ordinate indicates the presence of the low density material, to infer the presence and depth of steel bar in density, mainly focusing on the region of interest with the aid of characteristic behavior of the radiation with respect to the material density, analysis of the elements present in the graph confirms the characteristic behavior of the analysis within the statistical limit can be extended at a maximum of 60 mm with this experimental setup. The feasibility of penetration of the gamma radiation, over the extended depths (>60 mm) is possible in our experimental set up, if the source to sample distance is minimized. The detailed analysis of the elements present in the graph confirms the characteristic behavior of the radiation with respect to the material density, mainly focusing on the region of interest with the aid of sensitive volume, to infer the presence and depth of steel bar in the concrete mortar.

A further attempt to establish the orientation of the steel inclusions in the specimen has been carried on by placing the sample in the test bed. A single rod with 12 mm diameter and 50 mm height is inserted from the top portion of the concrete and a vertical scanning is performed along the direction of the insertion. The pulse height spectrum is recorded for every 10 mm step and the gross counts retrieved from the region of interest are plotted against the scanning distance (Fig. 9). The lower counts along the horizontal co-ordinate indicates the presence of the low density material (concrete) focused by the voxel volume and the region of the saturated counts designate the upright position of the high dense material (rebar) implanted in the concrete. The experimental evidence is furthermore extended to promote the established fact with 30 mm rod in the same layout. The only difference in the trend followed with respect to the previous case is the reduction of scattered intensity signal and the basis behind it, is due to the attenuation cum absorption of photons by 30 mm rebar. Since the Compton scattering cross-section is susceptible to the density of the target material, even the orientations of the inclusion are easily detectable with high sensitivity.

The variation of counts that is recorded in the energy bins of the pulse height spectrum for the rebar (12 mm diameter) and the concrete at the depth of 20 mm from the outlook of the sample is shown in Fig. 10. The photon backscatter measurements exhibit changes as the source beam scans across the test specimen. The graph clearly illustrates the detector response, wherein a sharper peak is seen for the rebar and a subdued peak for the concrete. The increase of counts as in the case of rebar is almost 23% when compared to concrete, for a precise voxel and this is due to the variation in the material density during the scanning and supports the previous arguments, leading to the indication and strong confirmation of presence of steel rebar embedded in the concrete. The measured differences between the materials offer a promising hold for the sensitivity of this technique for density spatial distribution within the test object.

5. Conclusion

Compton back scatter imaging is a relatively new and promising non-invasive NDE technology that is unique among ionizing radiations methods by requiring access to only one side of an object. The object is interrogated by a collimated gamma ray beam and the collimated detector measure the Compton scatter signal produced by each voxel. The acquired signal can be analyzed for evaluating the density, thickness and inhomogeneities present in the material as a function of position. In this paper, we have demonstrated its feasibility for the detection, orientation and spatial distribution of rebars in concrete. The depth of detection has been successfully extended up to 60 mm and the results have been correlated with the well established radiography method. While the present indigenously developed system is quite large, a miniature version would pave the way for its application in the field. This would open up possibilities for rebar corrosion detection, structural assessment including conservation of heritage structures by precisely locating inhomogeneities wherein prior knowledge of as-built drawings does not exist to identify the location of reinforcement during rehabilitation of the old buildings.

Acknowledgements

The authors thank Shri. S.A.V. Satya Murty, Director, Electronics, Instrumentation and Radiological Safety Group (EIRSG) and Dr. P.R. Vasudeva Rao, Director, Indira Gandhi Centre for Atomic
Research, Kalpakkam for their constant support and encouragement. Authors are also thankful to Dr.R.Baskaran, Shri N.Raghu and Quality Assurance Division colleagues for their support.

References