**Indian Society for**
**Non-Destructive Testing**
**Hyderabad Chapter**

**Proc. National Seminar on**
**Non-Destructive Evaluation**
**Dec. 7 - 9, 2006, Hyderabad**

# Theoretical Modeling of Digital Radiograph of Composite Rocket Nozzle for the Analysis of Defect

**C. Sreelekshmi[1], V.R. Ravindran[1] and V.P. Mahadevan Pillai[2]**
[1]Rocket Propellant Plant, Vikram Sarabhai Space Centre, Thiruvananthapuram-695 022
[2]Department of Opto-Electronics, Kariavattom, Thiruvananthapuram

## Abstract

Thick composite materials are used as liners in rocket nozzles, due to its structural strength, low density and very high thermal insulation property. Carbon fiber and Silica fiber based composite structures are used in the nozzles of large solid rocket motors. Since these are multiple layer structures, the commonly observed defects are delaminations, lack of adhesive material, porosity between layers etc. X-ray radiography techniques are generally used for the NDE of these composite nozzle liners. In this paper the theoretical modeling of radiographic images are carried out to provide input for interpretation of radiographs in silica phenolic composite nozzle liners. Details of software developed in $C^{++}$ language and its application to solve specific problems are discussed here.

**Keywords**: *X-ray radiography, Composite materials, Simulation*

## 1. Introduction

Radiographic inspection is widely used for the NDT of composite nozzle liners. It is difficult to distinguish and characterize the severity of defects such as porosity between layers, lack of adhesive material and minor delaminations by conventional qualitative methods of interpretation. It is mainly because the optical density variation corresponding to these defects will be indistinguishable. Quantitative analysis of optical density is essential to solve these problems. Mathematical modelling helps to standardise and generate methods to distinguish clearly the delamination, excess resin and lack of resin at the interfaces. Simulation of radiographic images for the quantitative non-destructive evaluation of solid rocket motors has been carried out in the earlier works [1]. The present study is mainly on the simulation of a composite nozzle liner with programmed defects. The approach adopted is to import the required information from the CAD data of the object. Software has been developed for the simulation of radiographic image in $C^{++}$ programming language. Using this software, radiographic images were generated and studied for the composite material.

## 2. Basic Principle

The model is a silica phenolic nozzle liner of average diameter of about 233 mm covering a total height of 330 mm (Fig. 1). This structure is fabricated by laying many layers of silica clothes and phenolic resin over a mandrel at a desired orientation and cured at high temperature and pressure. During this process the material undergoes severe stress conditions. So defects like delamination, gap between windings, resin lean region etc. can occur. Characterisation of defects by radiography is difficult due to this complex nature of the windings. By simulation of radiographic image, the effects of these defects in the radiograph can be predicted. The model considered for the study is shown in the figure below and the region marked 'a' is used for typical simulation. The thickness of the material at various radial locations are obtained from the CAD drawings (Fig 2).

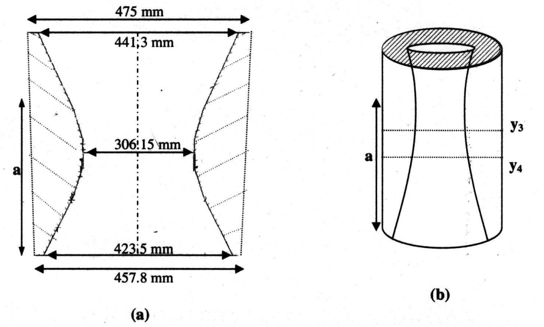

Fig. 1:(a) AUTOCAD drawing of the specimen (b) Schematic view of model used for simulation

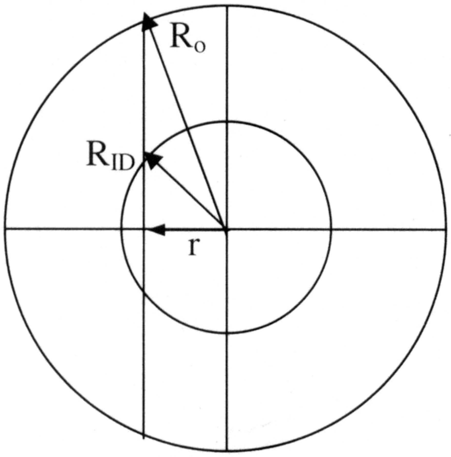

Fig. 2: Cross section of the object

The simulated image depends on the attenuation suffered by the x-ray beam. The intensity of X-ray beam reaching the image plane is attenuated linearly in the material. The attenuation suffered by the X-ray beam is given by the exponential equation [1&3].

$$I = I_0 \exp\left( -\sum_i \mu_i z_i \right) \qquad (1)$$

where '$\mu_i$' is the linear absorption coefficient and '$z_i$' is the effective thickness of the material `**i**´ in the X-ray beam path.`$I_o$´ is the incident X-ray intensity and '***I***' the transmitted intensity reaching the image plane. The optical density (D) corresponding to the effective X-ray exposure (E) reaching the recording film in the image plane is represented by the equation [1,2].

$$D = G \log_{10} E + k \qquad (2)$$

where, G is the gradient of the recording film,` k´ is a constant and`E´ is the exposure factor which is proportional to the radiation dose reaching the film after attenuation in the material. If the effect of the scatter factor and unsharpness are not considered the equation for optical density can be written as [1,2]

$$D = G\left[ \log I_0 - 0.434 \sum_i \mu_i z_i \right] + k \qquad (3)$$

The effective attenuation factor ($\Sigma_i \mu_i z_i$) in equation contributes to the optical density and subsequently to the gray level of each pixel in the image plane. The attenuation factor depends on the object geometry and presence of internal defects in the direction of X-ray beam.

## 3. Mathematical Modeling

The dimensional details of the model are given in Fig.1.a. The outer radius varies from 237.5 mm in the top to 228.9 mm at the bottom, while the inner radius variation is from 220.6mm to 211.75 mm. An approximate distance of 180 mm along the radial direction from OD is taken for simulation. The simulation programme covers a vertical height of about 245 mm from the bottom of the specimen.

The cross –section of the object at any point shows two circles as shown in Fig. 2. $R_0$ represents the radius of the outer region and $R_{ID}$ refers to the inner radius which varies along the length of the object.

For simulation, at each cross-sectional plane the inner diameter has to be calculated using the data drawn form AUTOCAD drawings. In this particular case, similarity of triangles method is used for the calculation of inner port radius ($R_{ID}$). The effective material thickness through which the x-ray beam traverses can be calculated using equations for region outside and inside the port ($C_i$) as

$$C_i = 2 \sqrt{(R_0^2 - r^2)} \quad (4)$$

$$C_i = 2 \{\sqrt{(R_0^2 - r^2)} - \sqrt{(R_{ID}^2 - r^2)}\} \quad (5)$$

respectively, where r is the variable along the radial location which covers the entire diameter of the object such that $0 < r < R_0$.

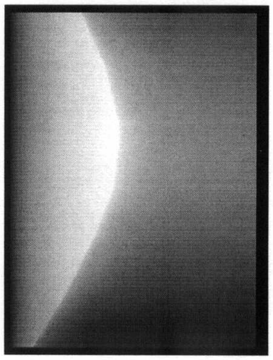

Fig.3: Simulated image of silica phenolic nozzle liner

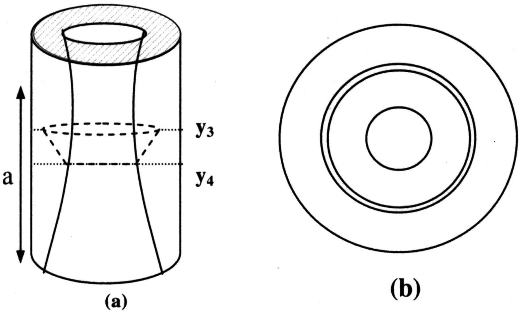

Fig. 4: (a) Object with defect b/w $y_3$ & $y_4$ (b) Cross section towards $y_3$

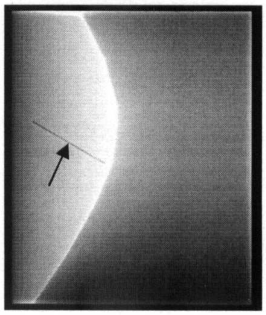

Fig. 5: Simulated image with defect (indicated by arrows)

The computer program is developed in $C^{++}$ programming language to generate the effective thickness and optical density corresponding to each pixel in the image. The parameters used for simulation are radius of outer case $R_0$ = 233 mm, film gradient G = 1, incident intensity $I_0$ = 1000 rads and linear absorption coefficient $\mu$ = 0.005775 $mm^{-1}$. These parameters are used to calculate the optical density, which is then converted into 8 bit gray level to display as digital image. The image is contrast stretched and inverted by the transformation equation [1]

$$S = \left( \frac{D - D_{\min}}{D_{\max} - D_{\min}} \right) x255 - 255 \quad (6)$$

where, S is the gray level of the contrast stretched image and D is the density at each point in the input image. The simulated image is of (512, 512) format with 256 gray levels. The simulated radiographic image is shown in Fig.3.

## 4. Simulation of X-Ray Image of the Model with Defects

The defect considered is a delamination of 2mm width at an orientation of $60^0$ with the axis extending upto the port. The model with defect between $y_3$ and $y_4$ and its cross-section at selected region are shown in Fig. 4a & 4b. The thickness in this case can be calculated using the relation.

$$Z_i = \sum E_i C_i \text{ , } i = 0,1,2,3 \quad (7)$$

$$C_i = 2\sqrt{(R_i^2 - r^2)} \qquad (8)$$

$E_i$'s being the equivalent thickness.

The object and its cross-section at selected region is shown in Fig. 4. The simulated radiographic image with defect is shown in Fig. 5.

## 5. Conclusion

The radiographic analysis of composite materials is difficult as it contains multiple layers of different materials. The method of simulation helps in distinguishing the delaminations, which are not possible with experimental radiograph. The method of simulation helps one to predict the nature of defect indication. Flaws of various shapes, sizes and material inclusions can be introduced for simulation, to produce reference images. The study on the effect of circumferential extension and width of the defect in the radiograph through optical density profile analysis is in progress. A study for generating quantitative information on the effect of defect at different radial location has also been taken up. The simulation software developed can be used for different type of composite materials for predicting the nature of defect, its depth and the type of material inclusion.

## 6. Acknowledgement

The authors wish to acknowledge the encouragement and support given by Sri. C B Kartha, Deputy Director, PRSO and Sri. S Alwan, General Manager, RPP of Vikram Sarabhai Space Centre, Trivandrum to carry out this work.

## 7. Reference

1. V.R.Ravindran, Jiji Joseph, “Computer Simulation of radiographic images for the quantitative evaluation of solid rocket motors”, Proceedings, National Seminar NDE -99, Vadodara,1999.
2. V.R.Ravindran,”Computer Simulation of the X-ray radiograph of an object under rotation and CT image reconstruction.”, Journal of NDT&E, Vol. 1 issue 2, 51-57, Sept- 2002.
3. R.Halmshaw, “*Non-destructive Testing*”, 2nd edition, 66-67, Edward Arnold, London, 1991.