Master's Thesis Defense

Geometric Analysis of Finite Difference Time Domain Simulation for Damage Assessment in Ground Penetrating Radar Applications

by
Burak Boyaci

Department of Civil and Environmental Engineering
University of Massachusetts Lowell

Advisor : Prof. Tzu-Yang Yu

06.10.2010

Outline

- Introduction
- Numerical Simulation
- Simulation Results
- Conclusions
- Future Work

Introduction

(Source: concrete-experts.com)

(Source: eng.cam.ac.uk)

(Source: loe.org)

(Source: partnershipborderstudy.com)

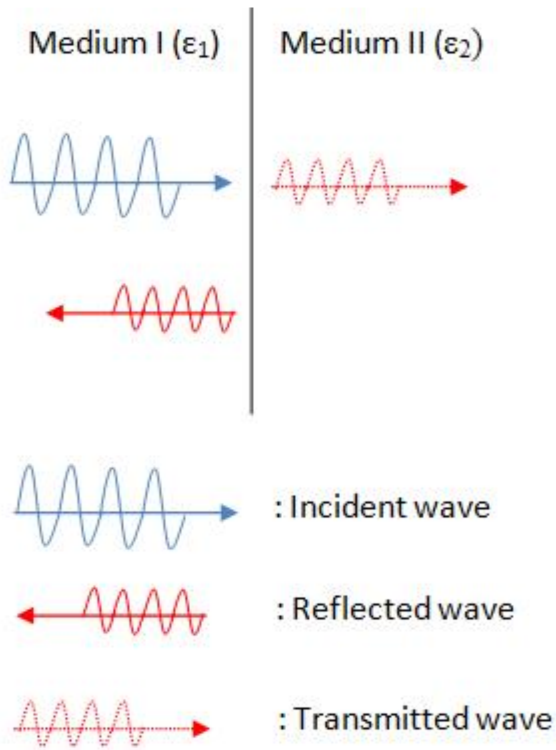
Introduction *(cont'd)*

- Nondestructive Testing (NDT): The appraisal of the condition of a material or structure without causing any damage to its functionality.

- Microwave/radar NDT methods
  - use transmission and reflection behaviors of electromagnetic waves.
  - are capable of conducting in-depth assessment of civil infrastructure systems such as concrete structures.

Introduction *(cont'd)*

- Electromagnetic waves are sensitive to the variation of dielectric properties of the medium in which they propagate.



Introduction *(cont' d)*

- Ground Penetrating Radar (GPR)

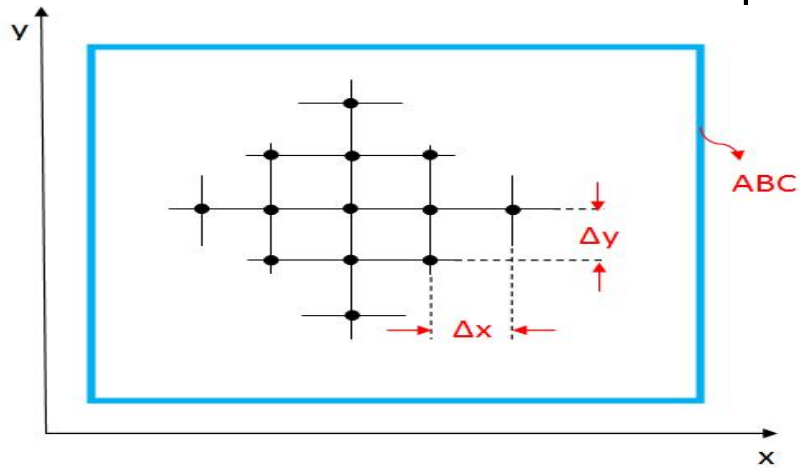
(source: GSSI)

Numerical Simulation

- In numerical simulations,
  - FDTD methods are used to solve Maxwell's curl equations.

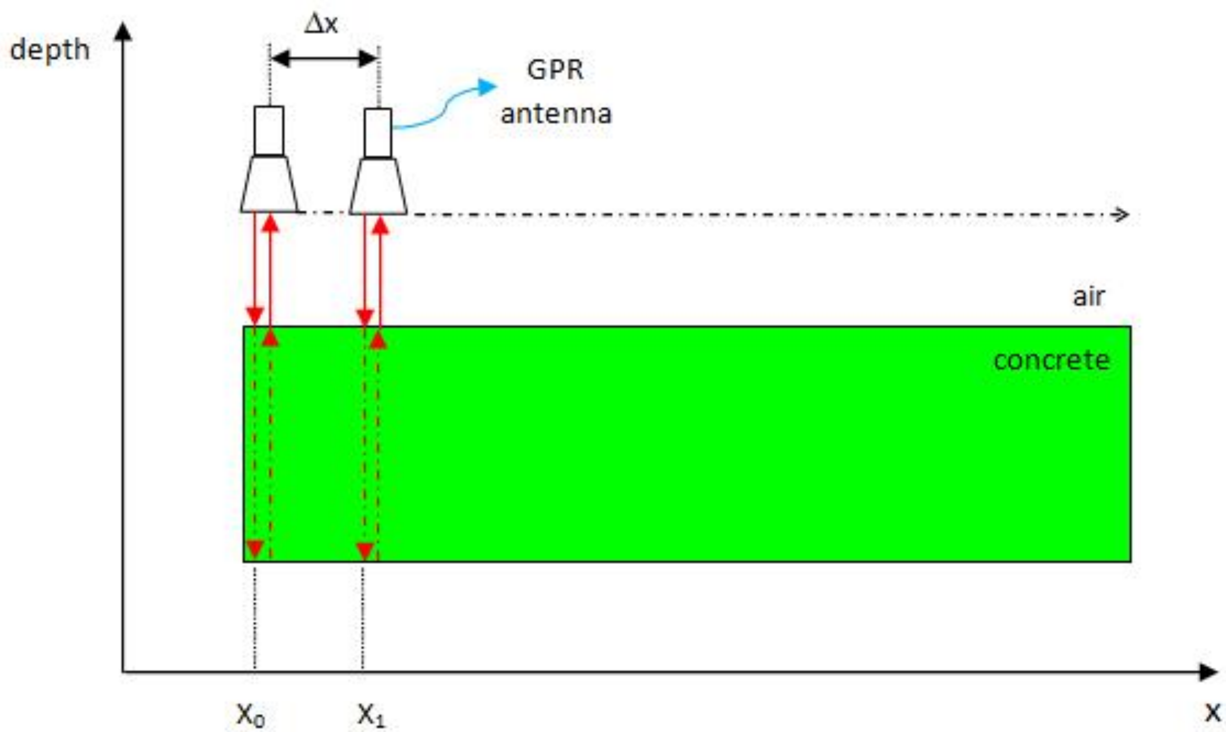
$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} + \sigma E_z \right)$$

  - absorbing boundary condition (ABC) is applied.
  - stability criteria is satisfied in discretization in space and time.



Numerical Simulation *(cont'd)*

- Simulation Scheme



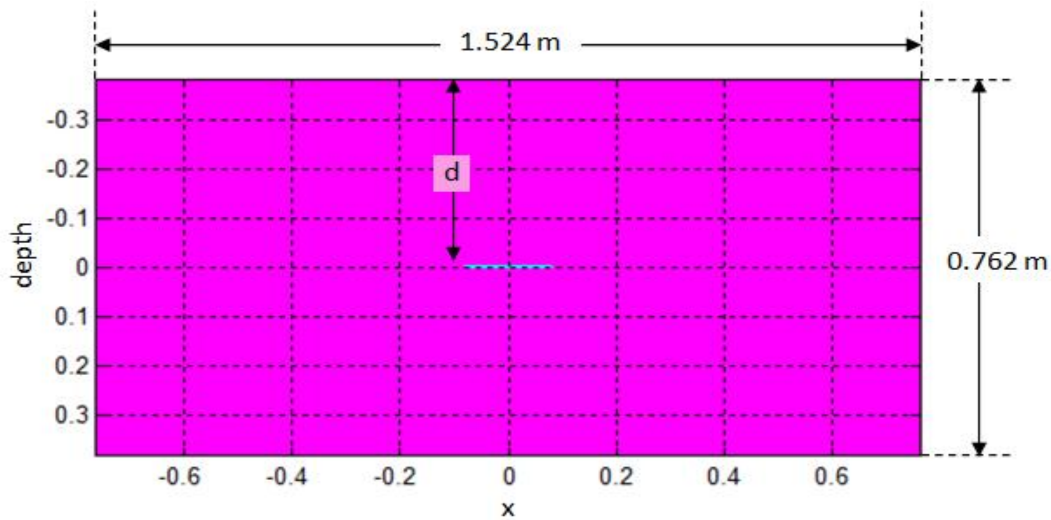
Numerical Simulation *(cont'd)*

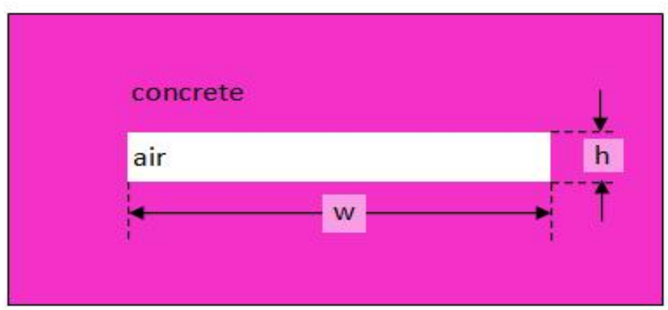
- Simulation Parameters

  - Dielectric constant of concrete, $\varepsilon_r' = 4$
  - Relative magnetic permeability of concrete, $\mu_r' = 1$
  - Conductivity of concrete, $\sigma=0$
  - Discretization in space $\Delta x = \Delta y = 2.54 \times 10^{-3} m < \frac{9c}{20\pi f} = 12.27 \times 10^{-3} m$
  - Discretization in time $\Delta t = 4.989 \times 10^{-12} s < \frac{\Delta x}{c\sqrt{2}} = 5.98 \times 10^{-12} s$
  - Excitation signal is a Gaussian impulse wave with a center frequency of 3.5 GHz

Numerical Simulation *(cont'd)*

- Simulation Cases

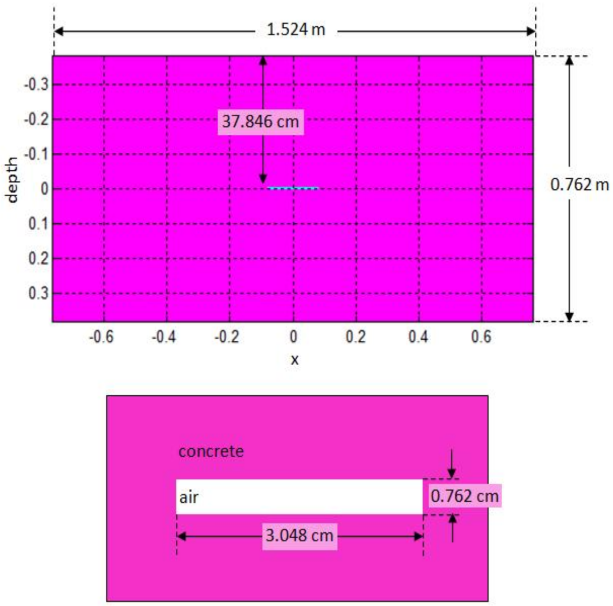




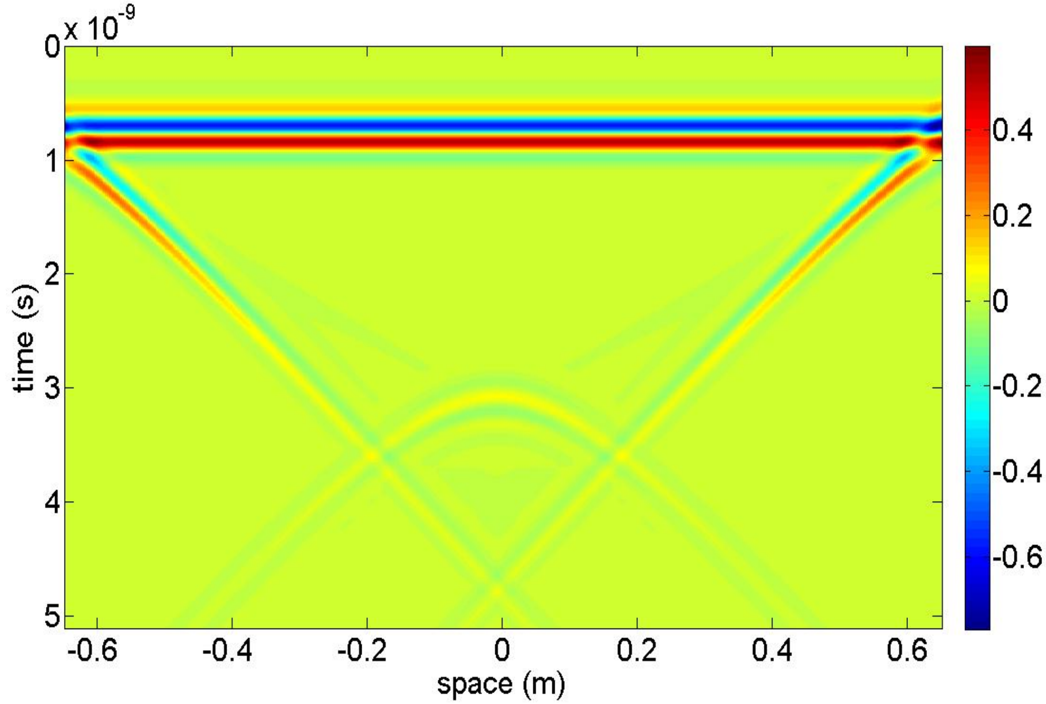
- h = 0.762 cm (3Δx)
- w = 3.048 cm (12Δx) ~ 16.256 cm (64Δx)
- d = 22.606 cm (89Δx) ~ 37.846 cm (149Δx)

Simulation Results

- Raw B-scan image



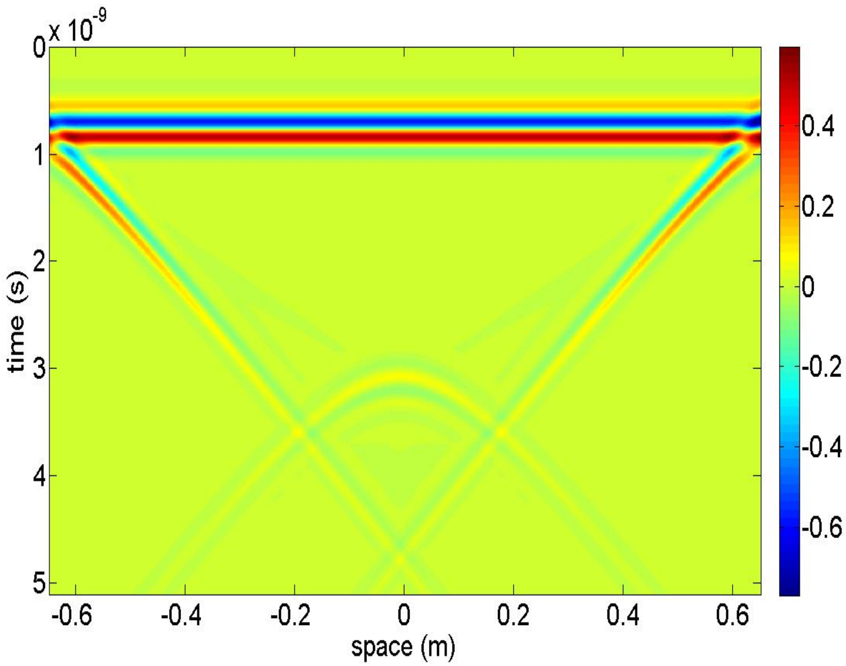
Raw B-scan image of concrete slab with a 3 cm-wide delamination at a depth of 37.846 cm



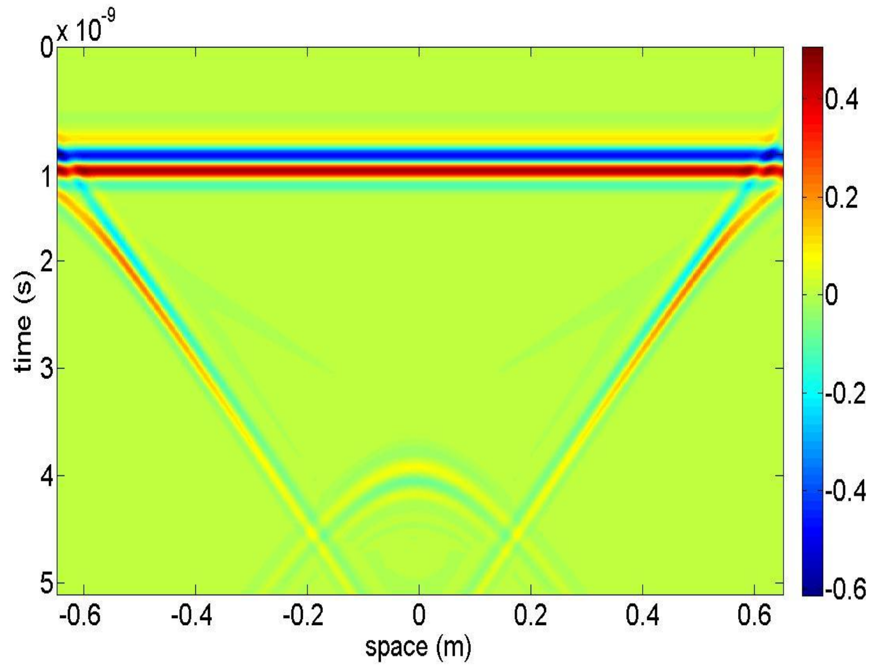
Simulation Results *(cont'd)*

- Comparison of slabs with different dielectric constants (ε_r')

Raw B-scan image of concrete slab with a dielectric constant of 4 (ε_r' =4)



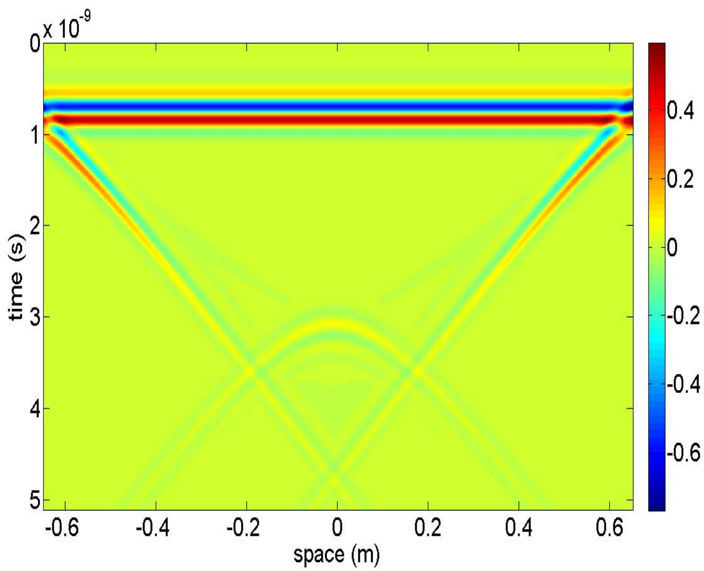
Raw B-scan image of concrete slab with a dielectric constant of 6 (ε_r' = 6)



Simulation Results *(cont'd)*

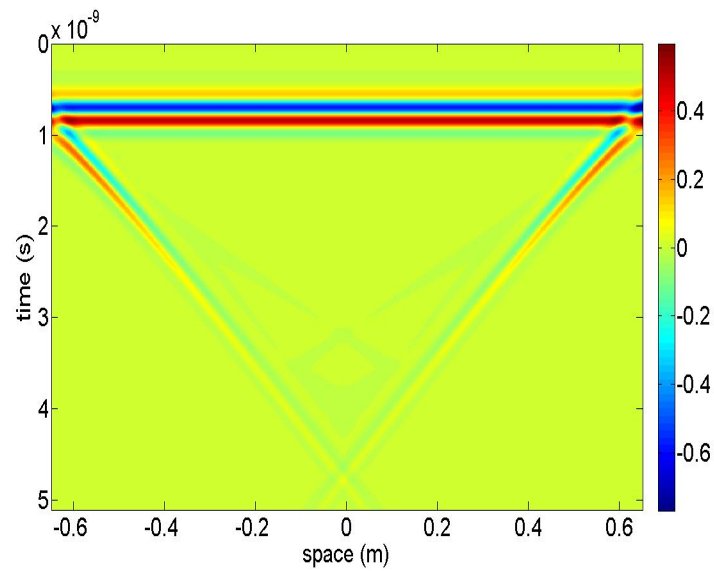
- Post-processing of raw B-scan images

Raw B-scan image of concrete slab with a 3 cm-wide delamination at a depth of 37.846 cm



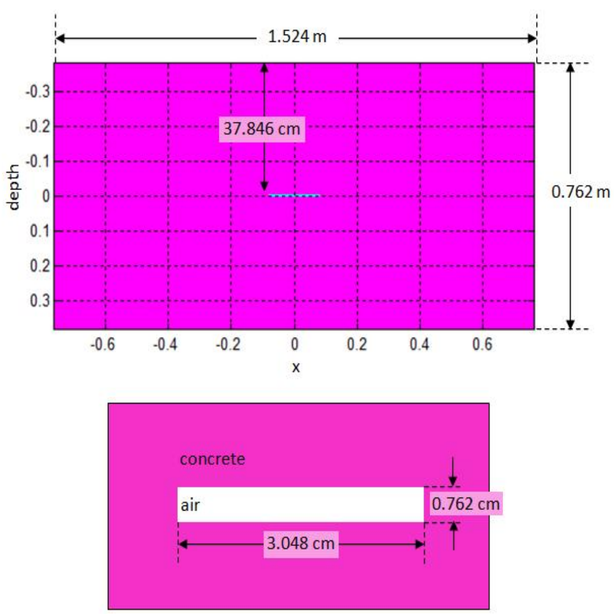
\- (minus)

B-scan image of concrete slab without delamination

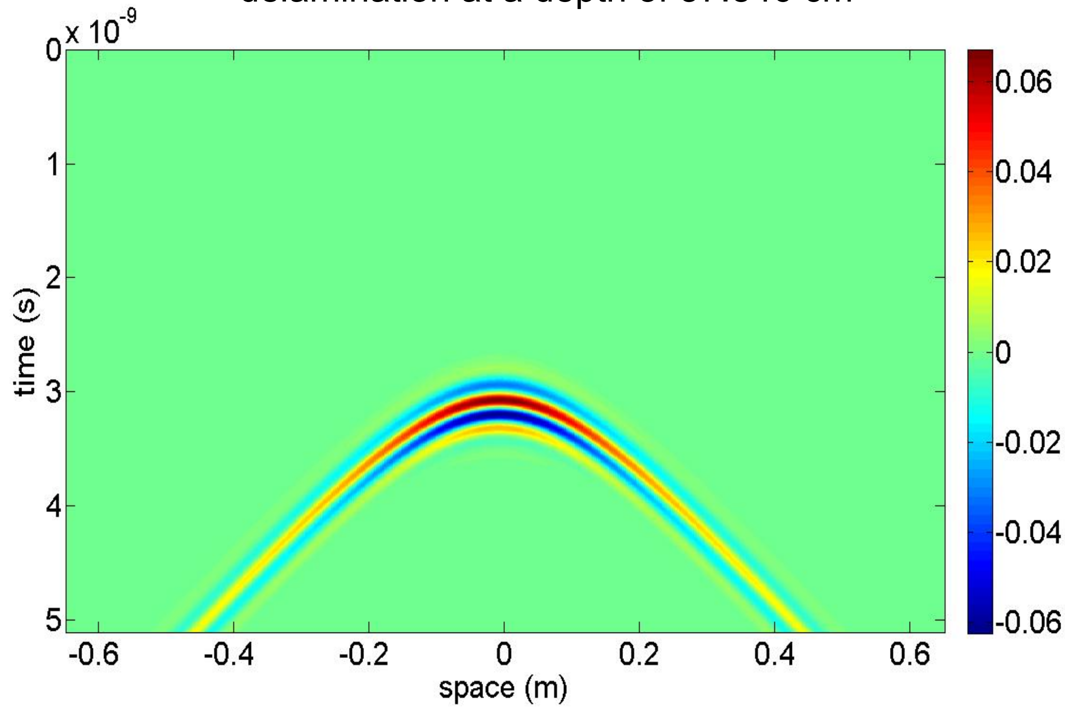


Simulation Results *(cont'd)*

- Clean B-scan image

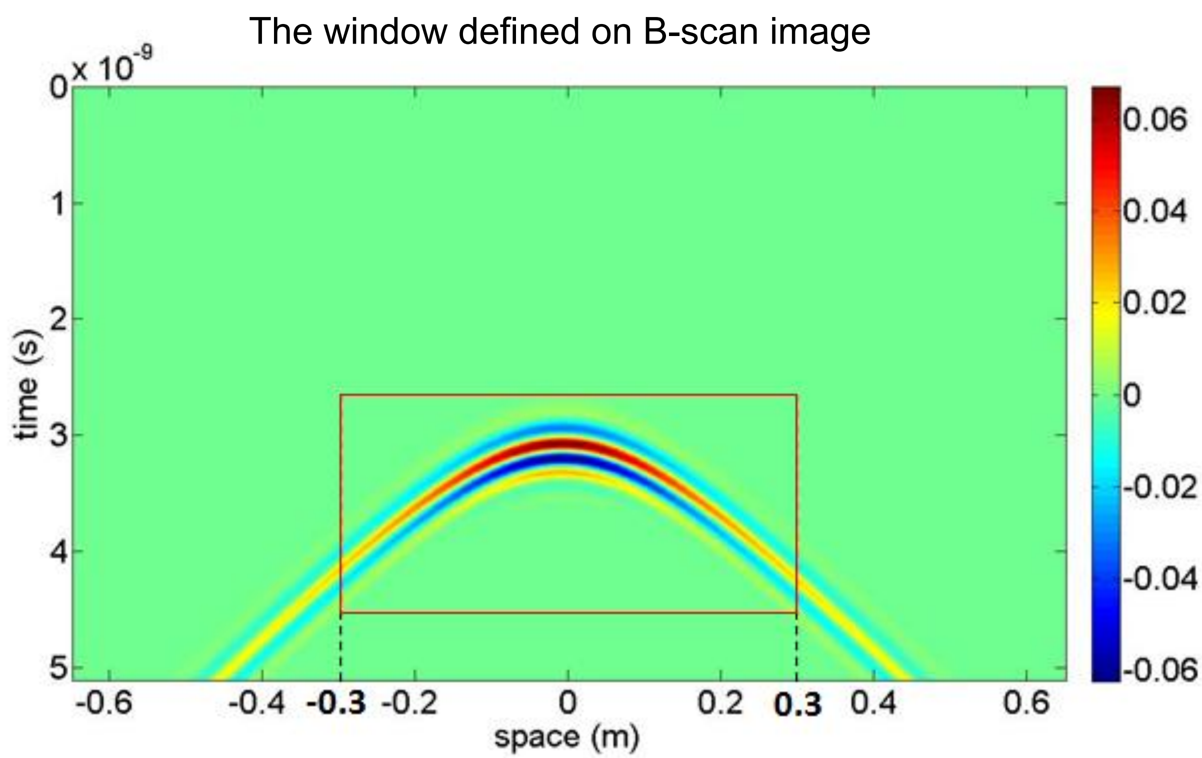


Clean B-scan image of concrete slab with a 3 cm-wide delamination at a depth of 37.846 cm



Simulation Results *(cont'd)*

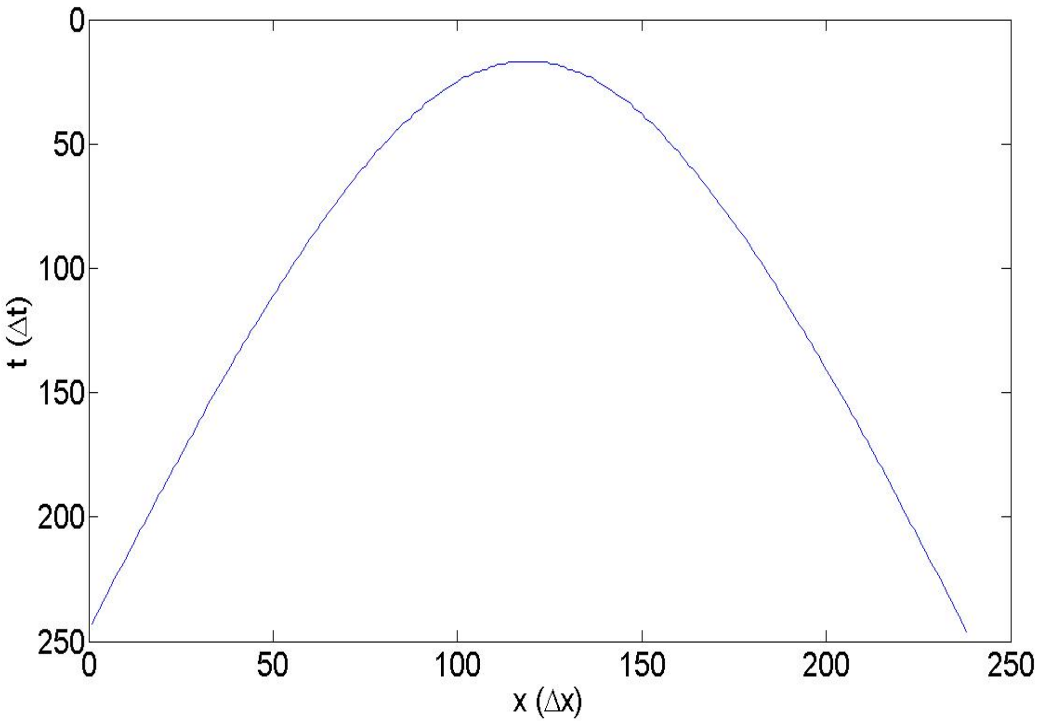
- Conversion of B-scan images to curve shapes



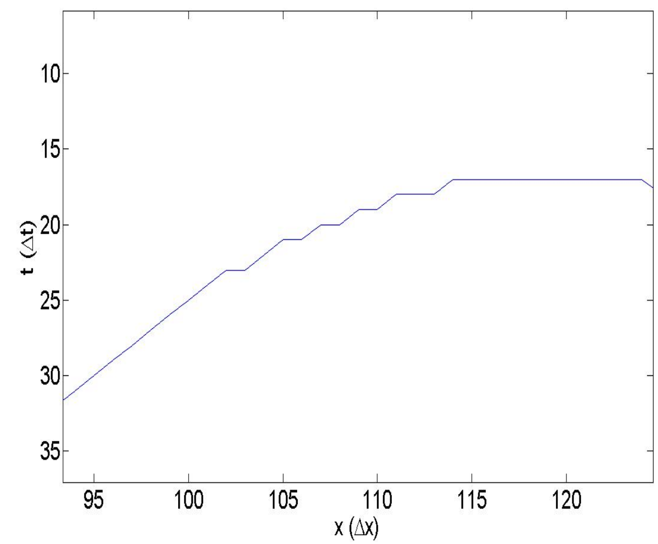
Simulation Results *(cont'd)*

- Conversion of B-scan images to curve shapes *(cont'd)*

The combination of maximum amplitude points on the window defined on B-scan image



Ripples on the curve shape



Simulation Results *(cont'd)*

- Conversion of B-scan images to curve shapes *(cont'd)*

Low-pass filter equations;

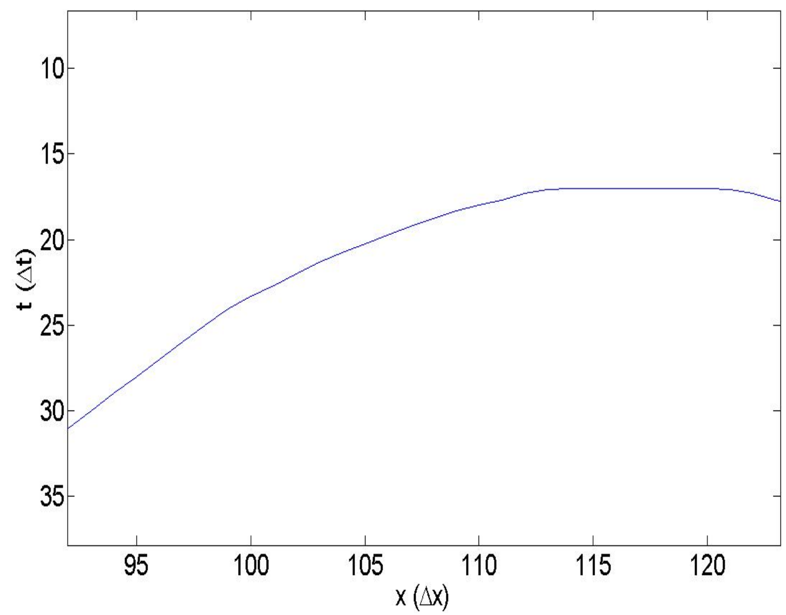
$$t'(x) = \frac{t(x) + t(x+1)}{2}$$

$$t''(x) = \frac{t'(x) + t'(x+1)}{2}$$

$$t'''(x) = \frac{t''(x) + t''(x+1)}{2}$$

$$t''''(x) = \frac{t'''(x) + t'''(x+1)}{2}$$

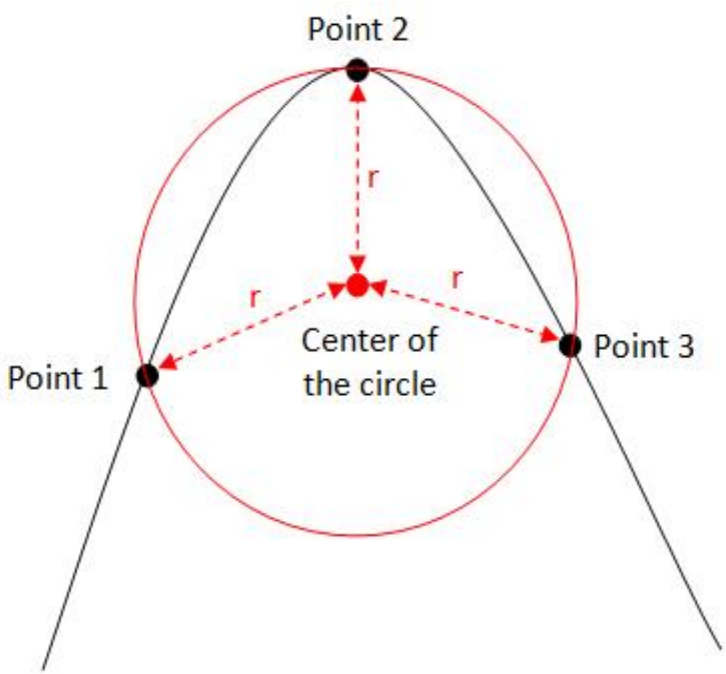
Smoothened ripples after filtering



Simulation Results *(cont'd)*

- Curvature Calculations

The circle passing through the three points of a curve



$$k = \frac{1}{r}$$

where;

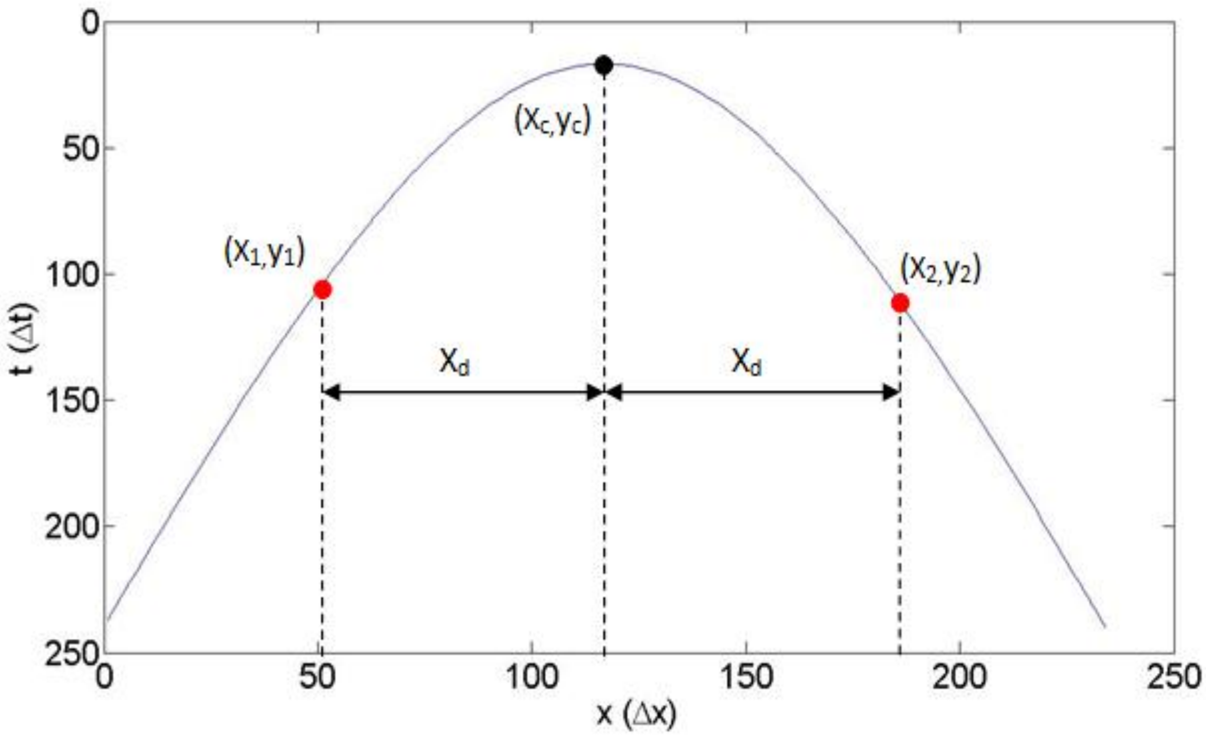
k : curvature

r : radius

Simulation Results *(cont'd)*

- Curvature Calculations *(cont'd)*

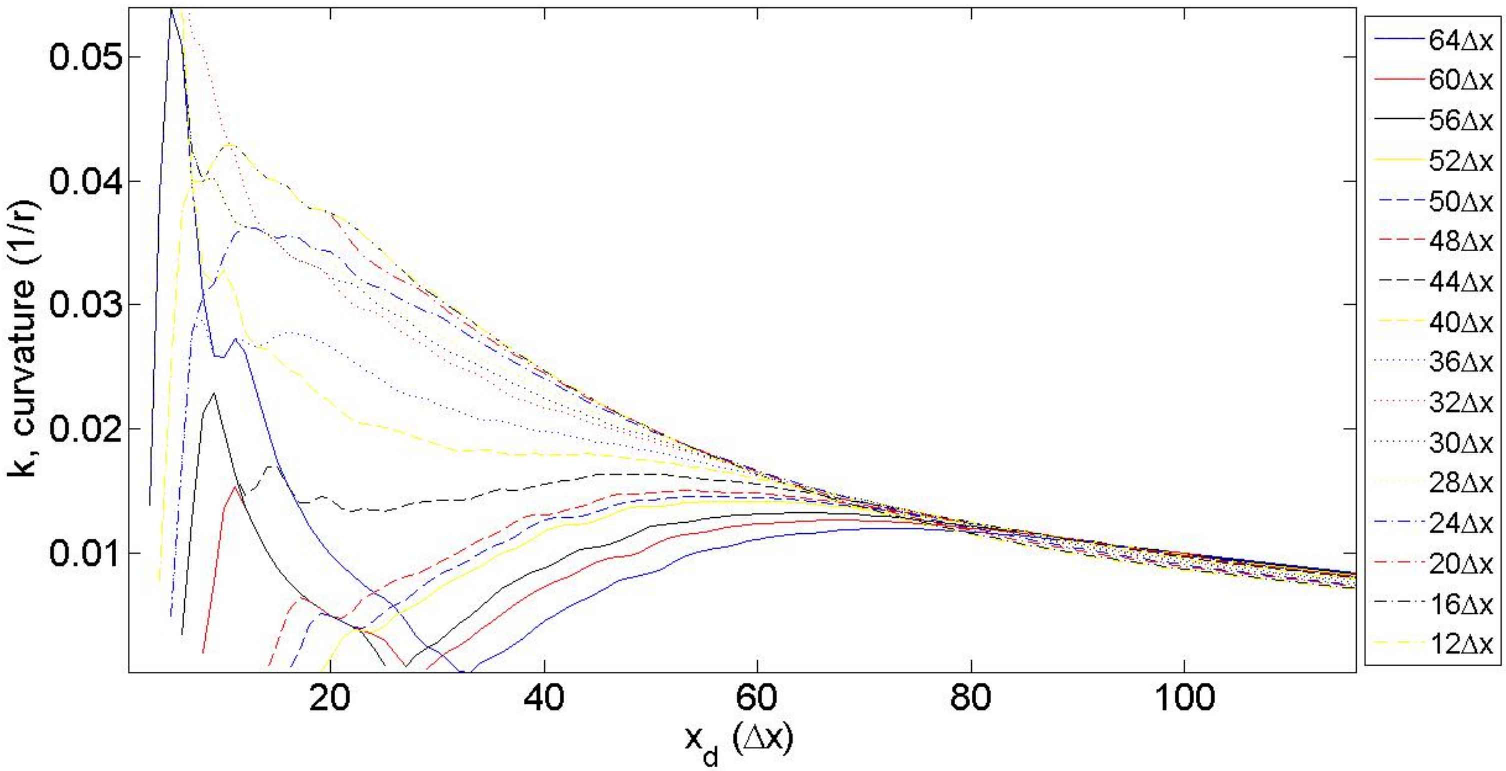
Selection of three points on curve shapes for curvature calculations



Simulation Results *(cont'd)*

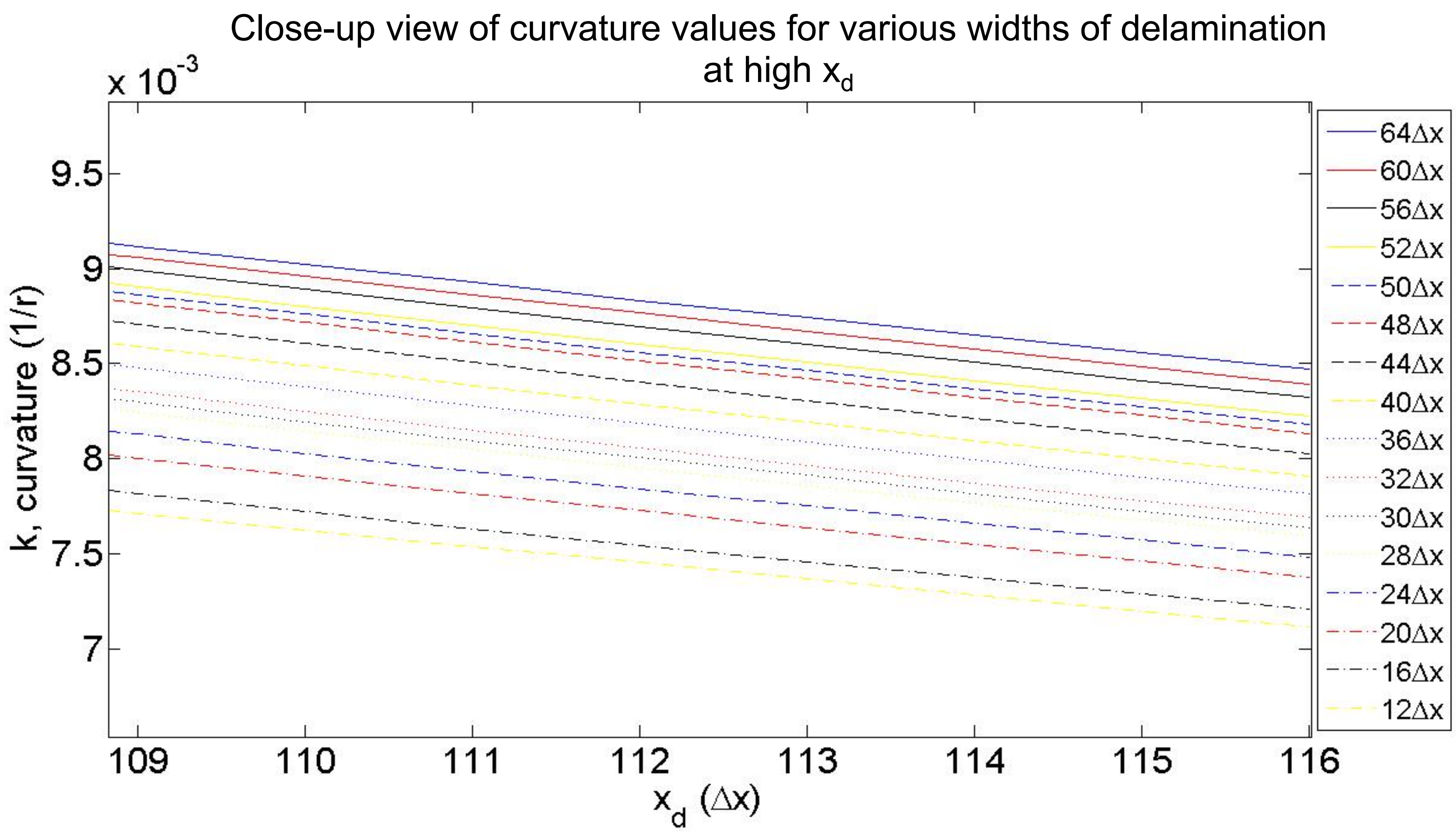
- Curvature Calculations *(cont'd)*

Curvature values of curve shapes (reflection responses of various widths of delamination at a depth of 37.8 cm)



Simulation Results *(cont'd)*

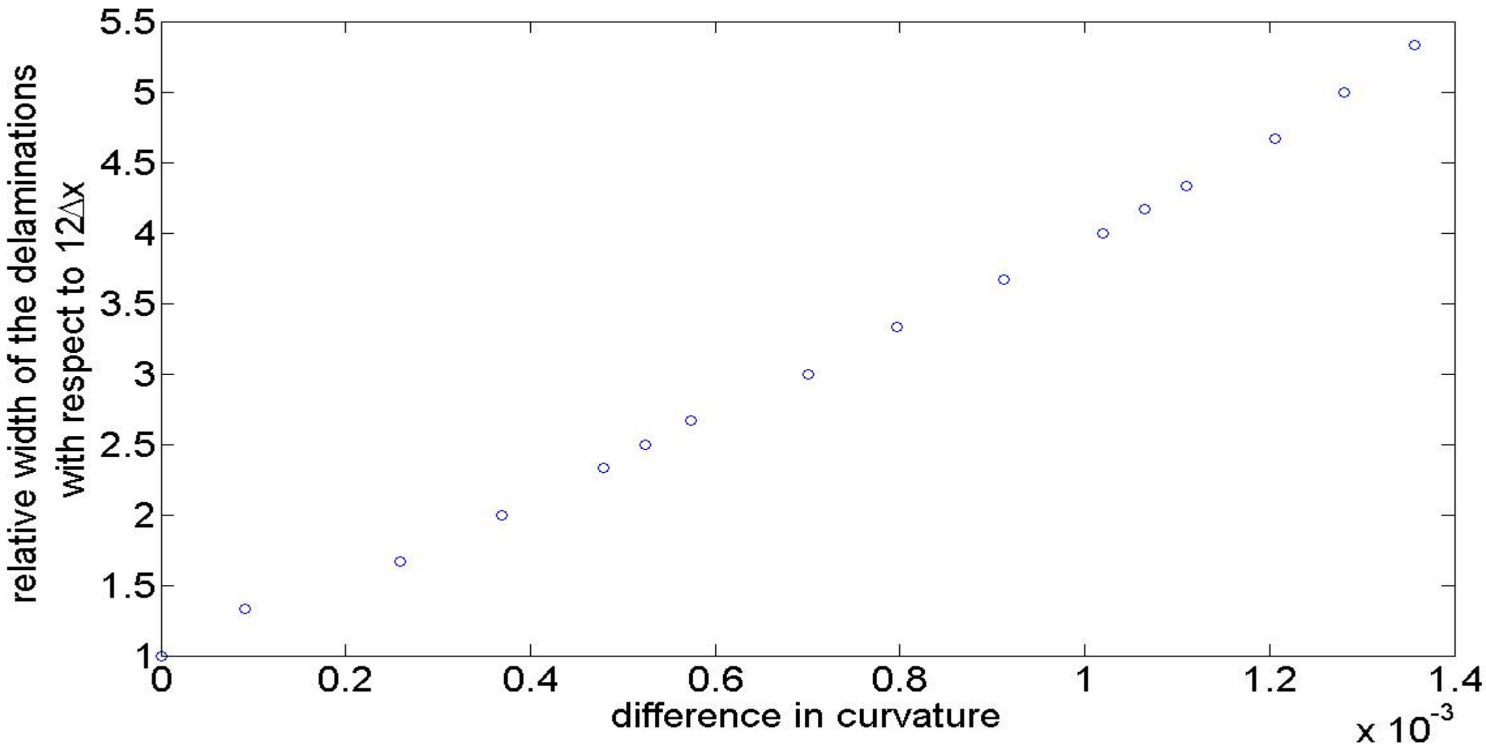
- Curvature Calculations *(cont'd)*



Simulation Results *(cont'd)*

- Relationship between the curvature and the width of delamination

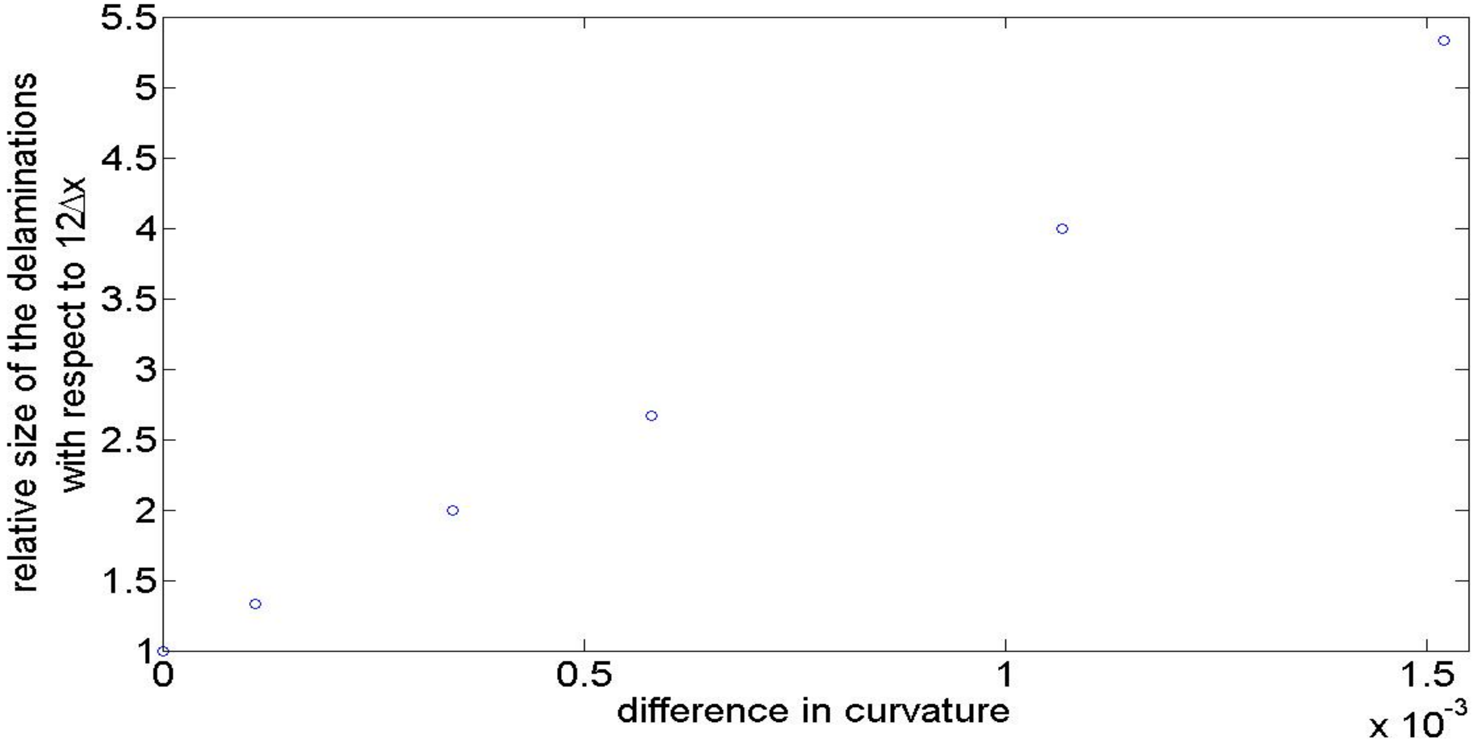
Difference in curvature values versus relative width of the delaminations at a depth of 37.8 cm



Simulation Results *(cont'd)*

- Relationship between the curvature and the width of delamination *(cont'd)*

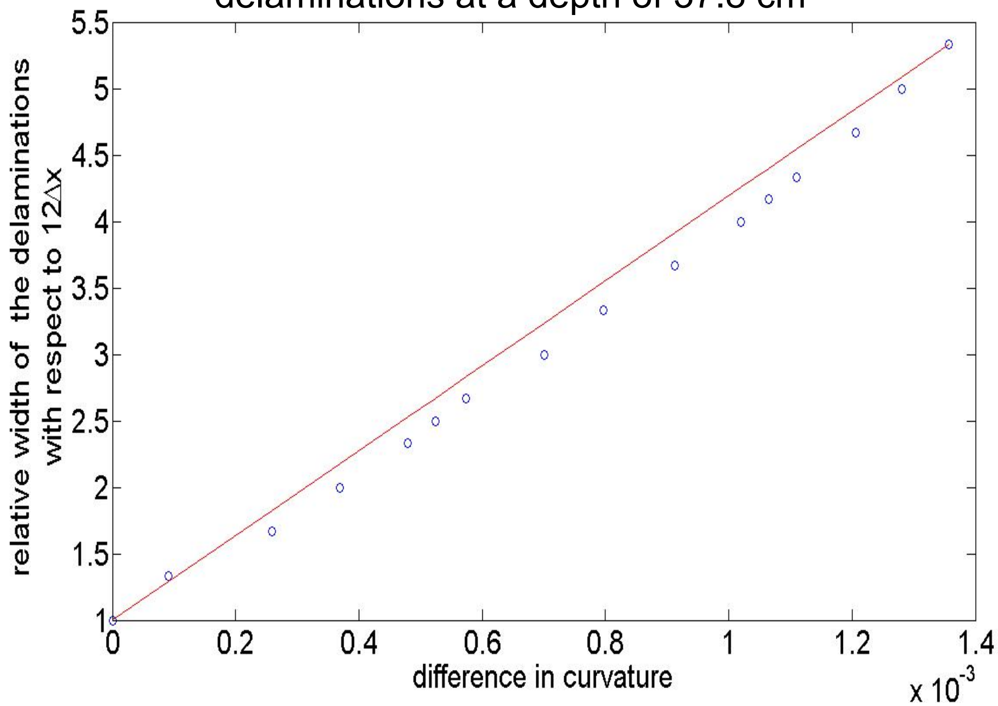
Difference in curvature values versus relative width of the delaminations at a depth of 27.6 cm



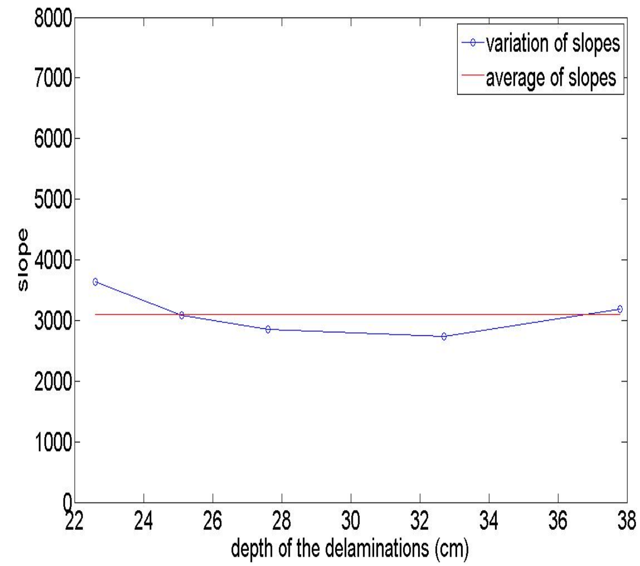
Simulation Results *(cont'd)*

- Relationship between the curvature and the width of delamination *(cont'd)*

The line connecting the first and last data point for the delaminations at a depth of 37.8 cm



Slopes of the lines for data sets at different depths



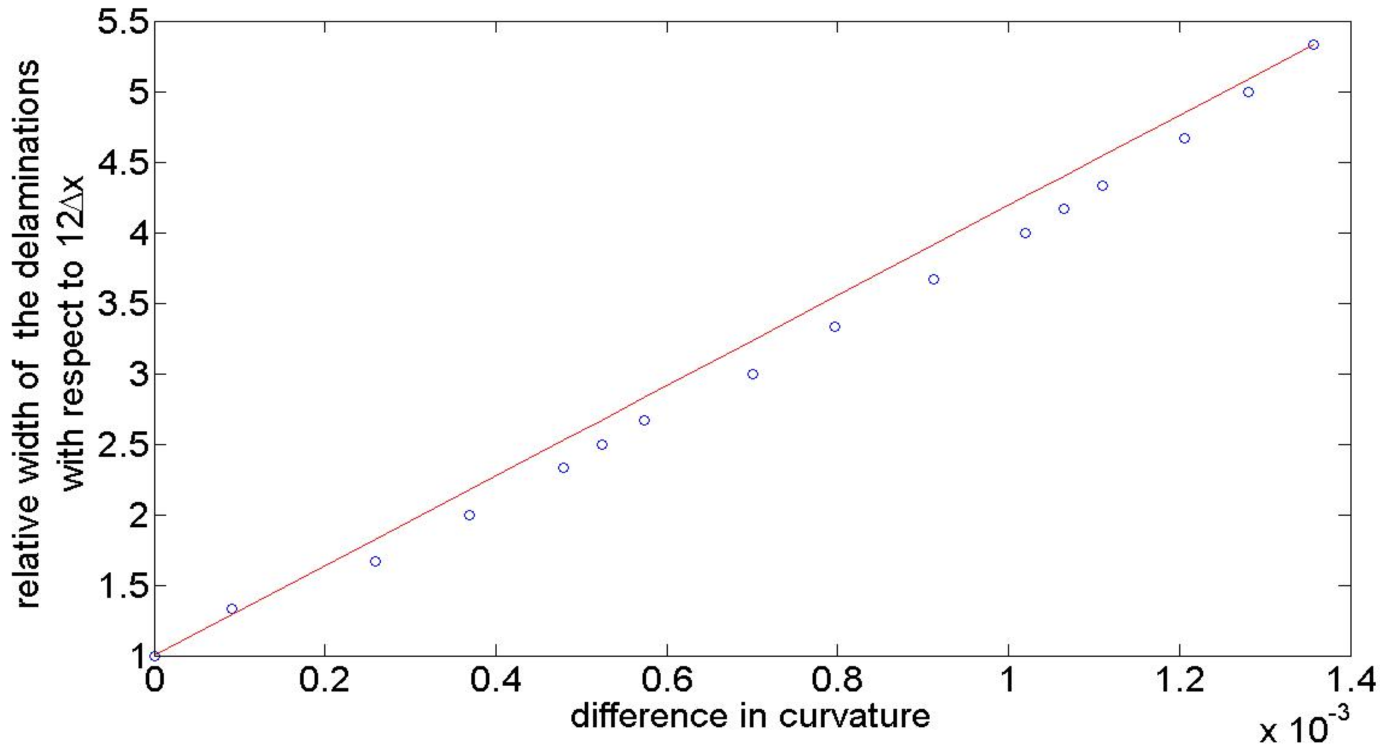
Simulation Results *(cont'd)*

- Curve fitting to results
  - Linear Fitting
    1. Easy fit line
    2. Best fit line
    3. Optimized line
  - Quadratic Fitting
  - Cubic Fitting

Simulation Results *(cont'd)*

- <u>Easy fit line</u> : A line connecting the first and last data point

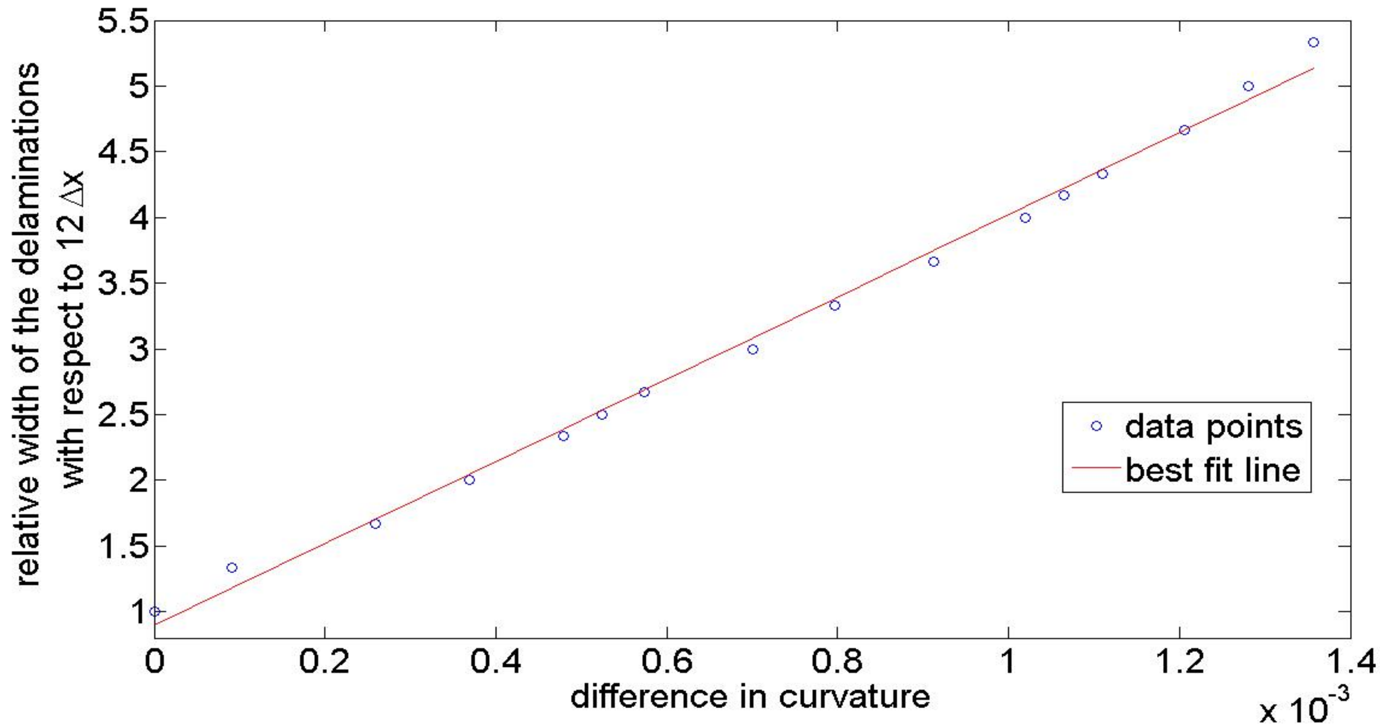
$$W_r = 3193 \times \Delta k + 1$$



Simulation Results *(cont'd)*

- <u>Best fit line</u> : A line statistically providing the minimum standart deviation

$$W_r = 3124 \times \Delta k + 0.89$$

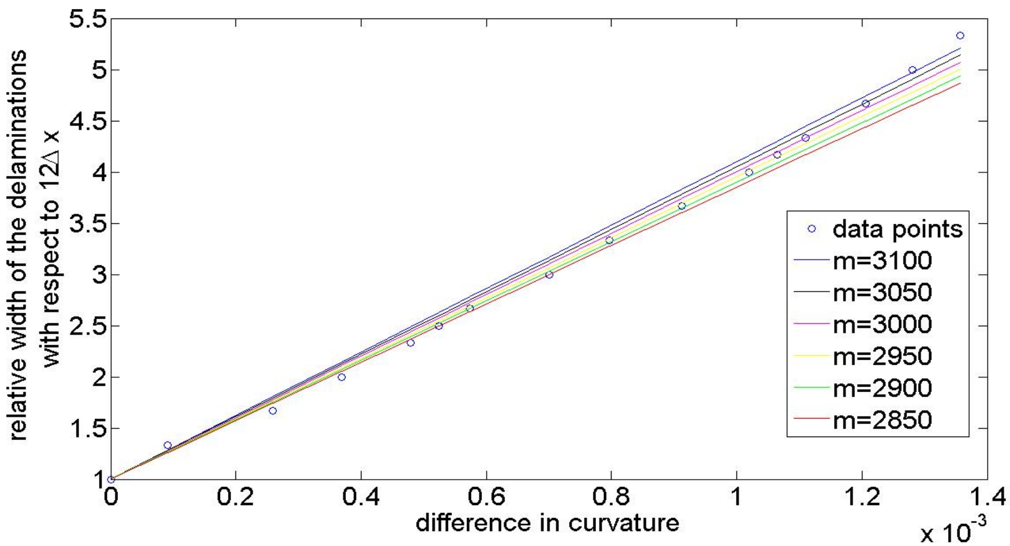


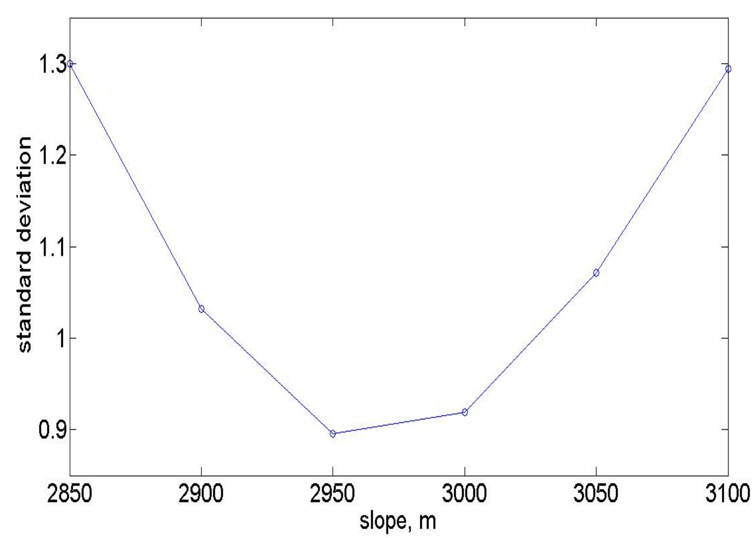
Simulation Results *(cont'd)*

- Optimized Line

$$W_r = m \times \Delta k + 1$$

- second term on the right side of the equation is set to be 1
- different m values are tried



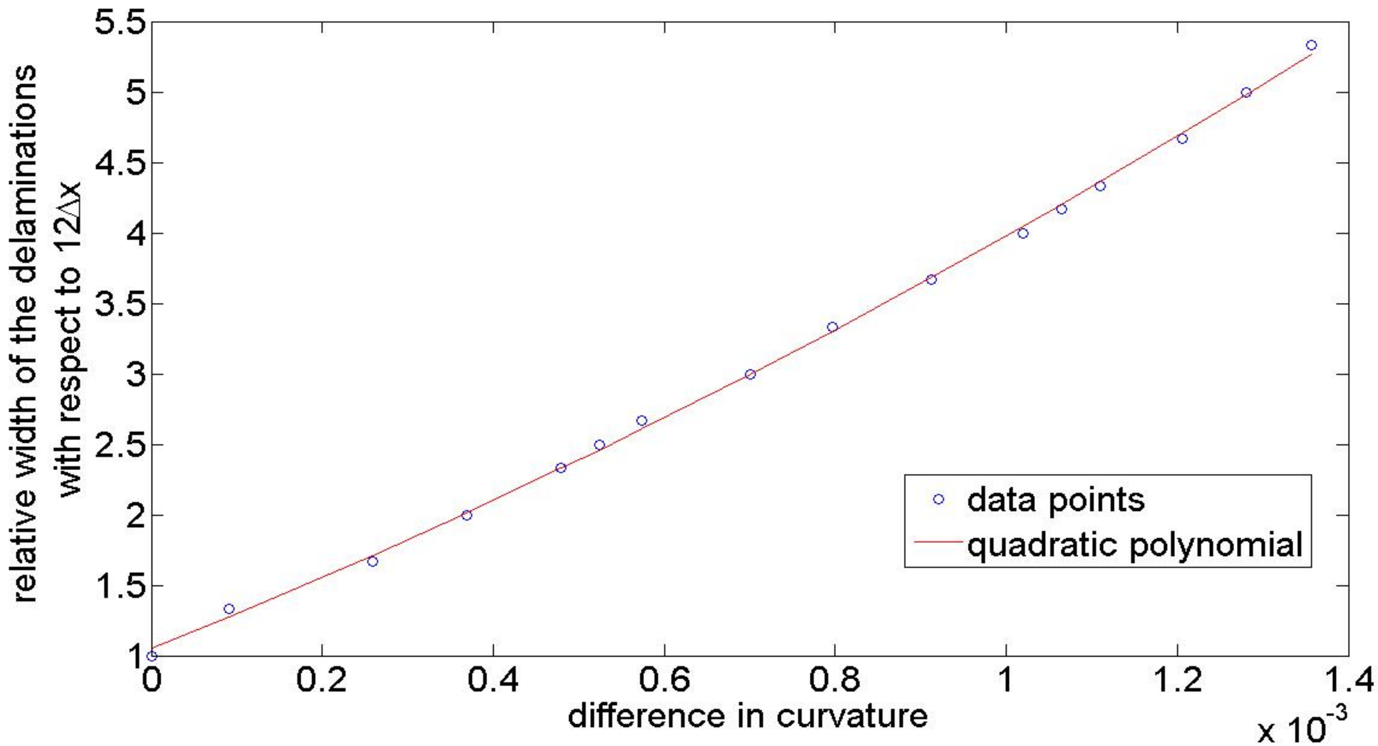


$$W_r = 2950 \times \Delta k + 1$$

Simulation Results *(cont'd)*

- Quadratic fitting

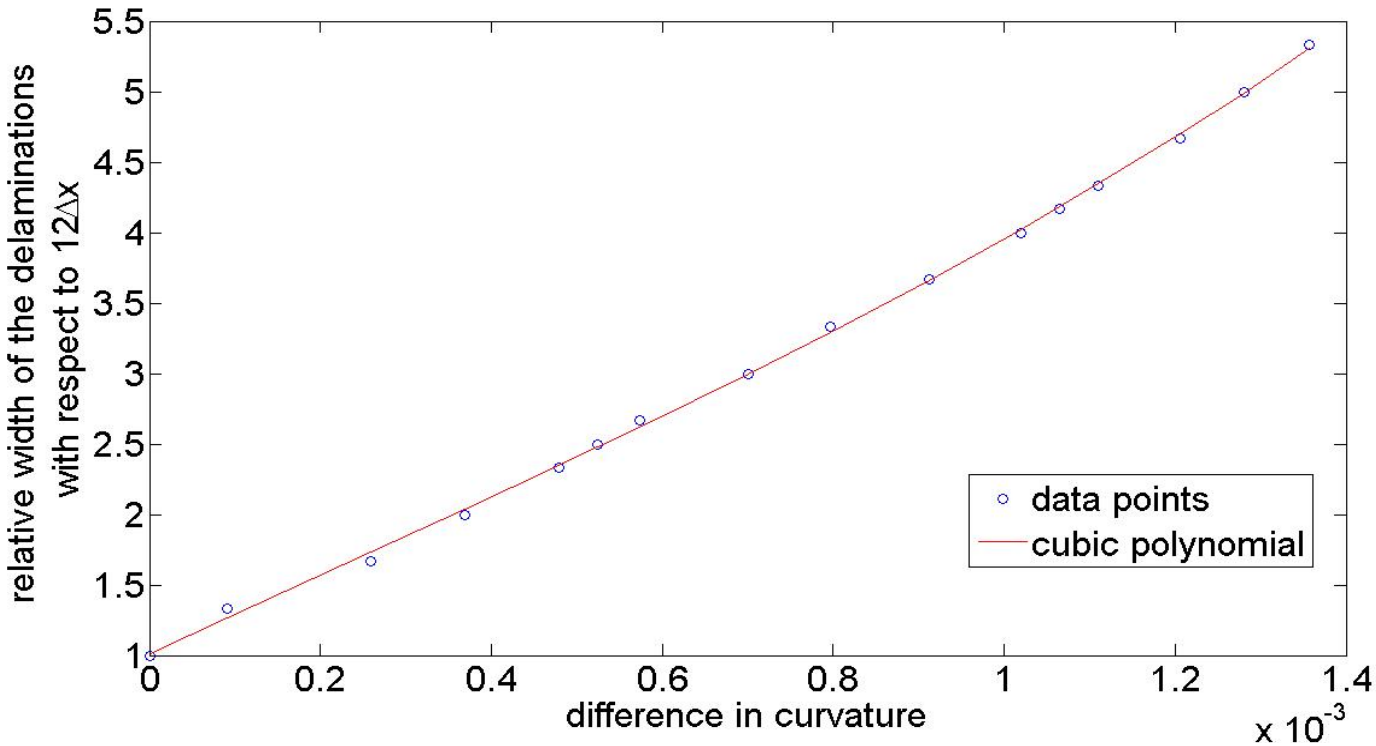
$$W_r = 4.967 \times 10^5 \times \Delta k^2 + 2435 \times \Delta k + 1.047$$



Simulation Results *(cont'd)*

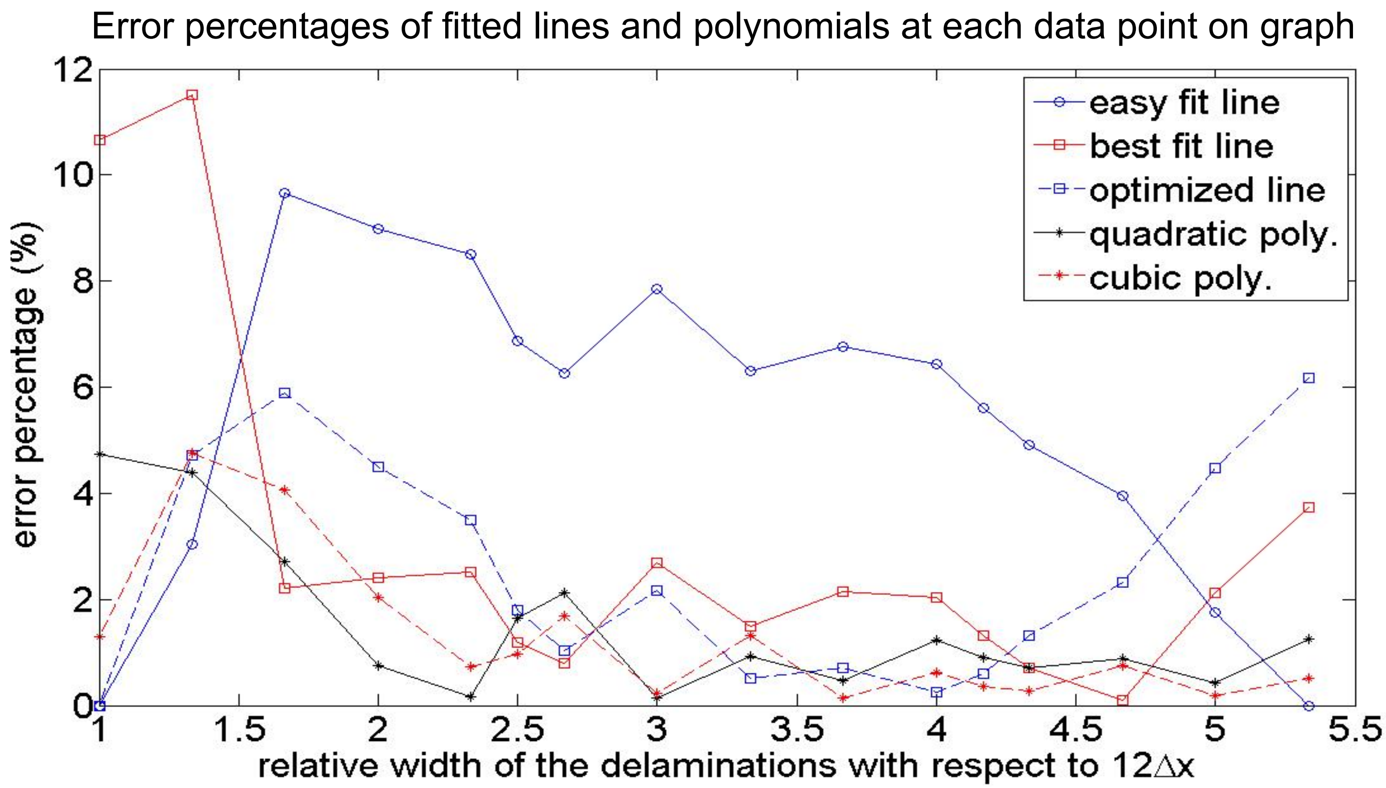
- <u>Cubic fitting</u>

$$W_r = 4.967\times10^8\times\Delta k^3 - 2.553\times10^5\times\Delta k^2 + 2825\times\Delta k + 1.013$$



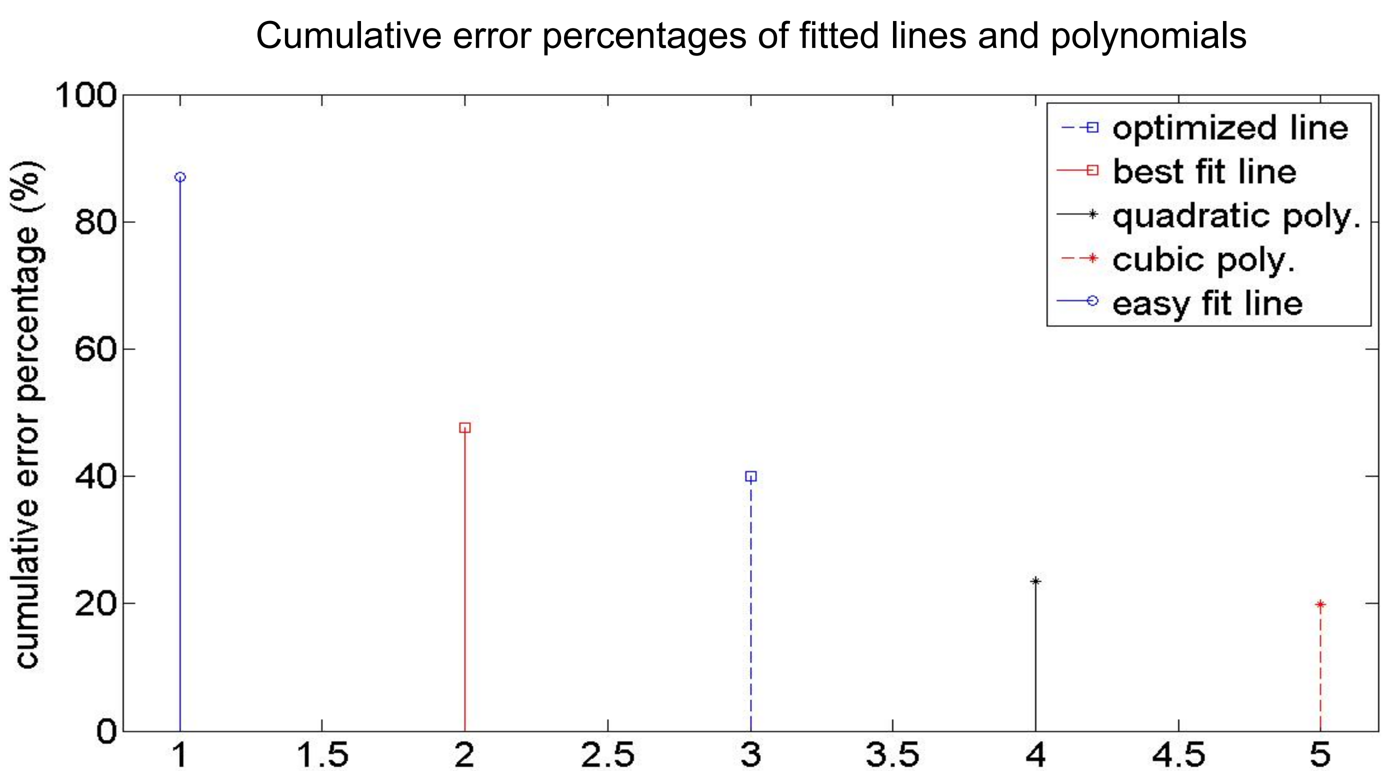
Simulation Results *(cont'd)*

- Error calculations



Simulation Results *(cont'd)*

- Error calculations *(cont'd)*



Simulation Results *(cont'd)*

- The best approximations for representing the relationship between curvature values (k) and width of delaminations (W) are ;

i. Optimized Line

$$W_r = 2950 \times \Delta k + 1$$

ii. Cubic Polynomial

$$W_r = 4.967 \times 10^8 \times \Delta k^3 - 2.553 \times 10^5 \times \Delta k^2 + 2825 \times \Delta k + 1.013$$

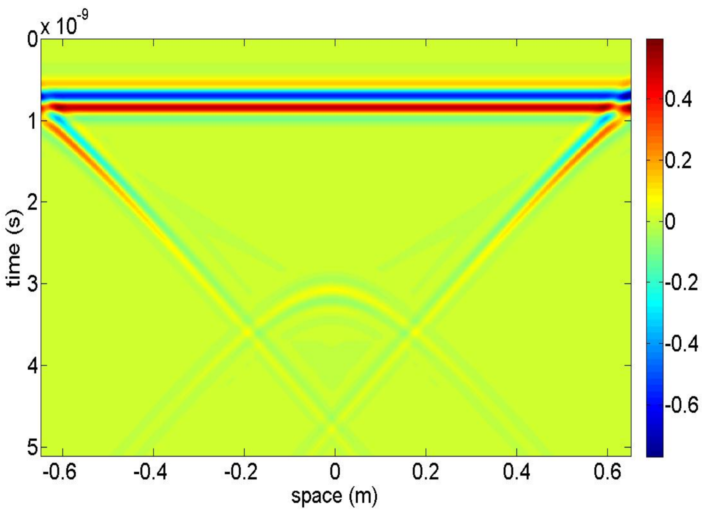
where

$$W_r = \frac{W}{W_{ref}} \quad \text{and} \quad \Delta k = k - k_{ref}$$

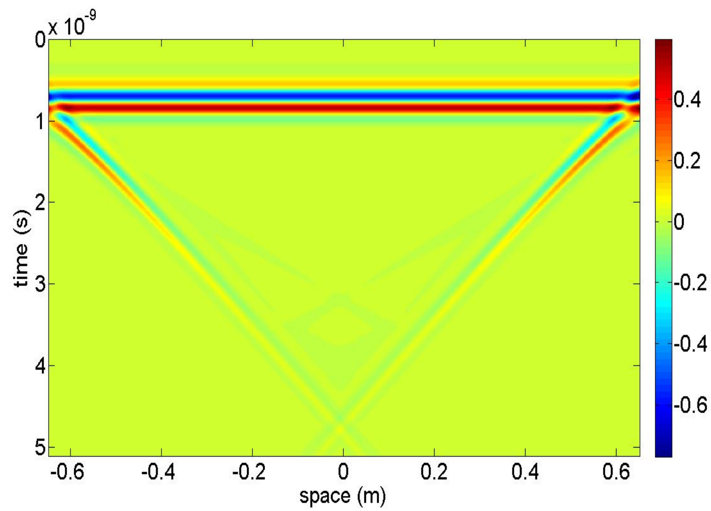
Simulation Results *(cont'd)*

- Steps of a procedure for estimating the width of subsurface delaminations :

  1. Obtain the "raw B-scan image" of concrete slab with a delamination.
  2. Obtain the B-scan image of concrete slab without delamination.
  3. Subtract the B-scan image of concrete slab without delamination from the "raw B-scan image".



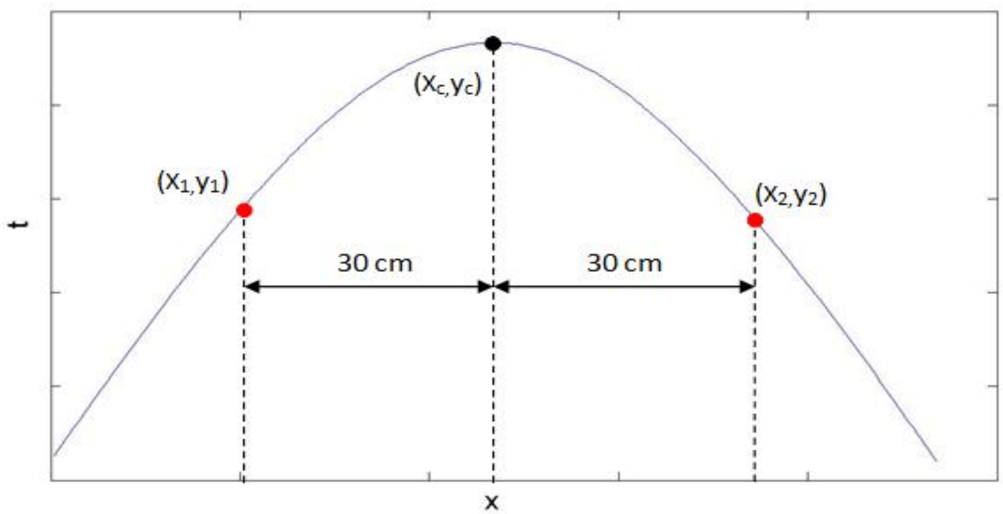
\-
(minus)



Simulation Results *(cont'd)*

- Steps of a procedure for estimating the width of subsurface delaminations :

4. Extract a simple curve shape from the modified B-scan image.
5. Apply a low-pass filter to smoothen the curve shape.
6. Calculate the curvature value (k) using three data points (one at the peak and other two at 30 cm away from the peak in –x and +x directions).



Simulation Results *(cont'd)*

- Steps of a procedure for estimating the width of subsurface delaminations :

  7. Estimate the width of the delamination by calculating the curvature value of reference delamination with a known width and using one of the following equations.

$$W_r = 2950 \times \Delta k + 1$$

$$W_r = 4.967 \times 10^8 \times \Delta k^3 - 2.553 \times 10^5 \times \Delta k^2 + 2825 \times \Delta k + 1.013$$

where

$$W_r = \frac{W}{W_{ref}}$$ and $$\Delta k = k - k_{ref}$$

Simulation Results *(cont'd)*

- An example of width estimation of delamination

1) Given ;
   W_{ref} = 3 cm and k_{ref} = 0.01

2) Calculation k of the unknown delamination by applying the procedure;
   k = 0.0105

3) Calculation of Δk ;
   $$\Delta k = k - k_{ref} = \boxed{5 \times 10^{-4}}$$

4) Calculation of W_r ;
   $$W_{r1} = 2950 \times \Delta k + 1 = \boxed{2.475}$$
   $$W_{r2} = 4.967 \times 10^8 \times \Delta k^3 - 2.553 \times 10^5 \times \Delta k^2 + 2825 \times \Delta k + 1.013 = \boxed{2.363}$$

5) Calculation of W ;
   $$W_r = \frac{W}{W_{ref}} \longrightarrow W_1 = \boxed{7.425 \quad cm} \qquad W_2 = \boxed{7.089 \quad cm}$$

Conclusions

- A simulation work modeling GPR applications for damage assessment of concrete structures is conducted using FDTD methods.
- Geometric analysis of simulation results is performed for defect size estimation.
- Relationship between Δk and W_r is found to be almost linear regardless of the depth of delamination.
- A procedure for estimating the width of subsurface delaminations in concrete slab is developed. Two equations are proposed.
- To apply the developed procedure;
  - concrete slab must be scanned at least 30 cm before and until 30 cm away from the center of the delamination.
  - dielectric constant of concrete must be 4 ($\varepsilon_r' = 4$).

Future Work

- Different dielectric constants of concrete can be considered.
- Delaminations with different orientations can be examined.
- Circle scatterers representing rebars can be defined to develop another procedure for estimating the size of rebars.