Rock Bolt Condition Monitoring Using Ultrasonic Guided Waves

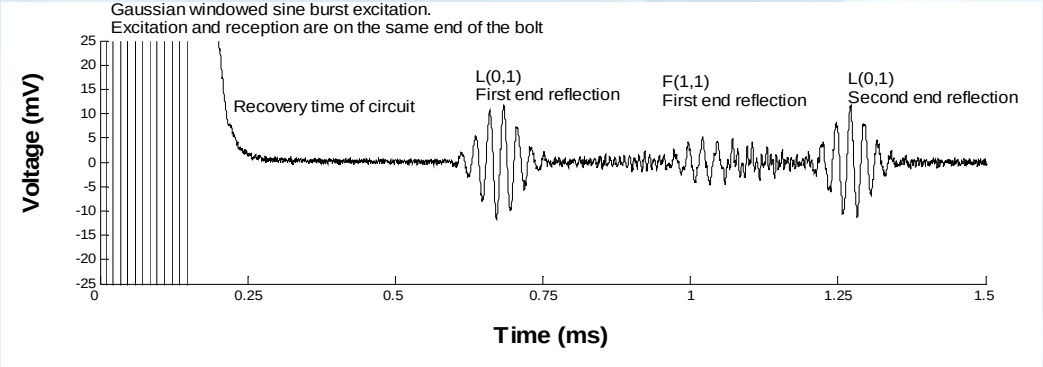
Bennie Buys

Department of Mechanical and Aeronautical Engineering

University of Pretoria

Introduction

- Rock Bolts and their associated problems
- Available Integrity Testing Methods
- Guided Ultrasonic Waves
- Experimental Setup
- Early investigations
- Simulating and testing 2 mayor defects
- Conclusion and recommendations



Scope of work

- Investigation into rock bolts and their associated defects and available NDT testing methods.
- Developing a fundamental understanding of ultrasonic waves and FEA modelling of wave propagation.
- Simulating an unbounded rock bolt using Finite Elements and comparing it to analytical wave equation results.
- Comparing the Experimental unbounded bolt to the FEA model.

Scope of work

- Perfectly embedded bolts

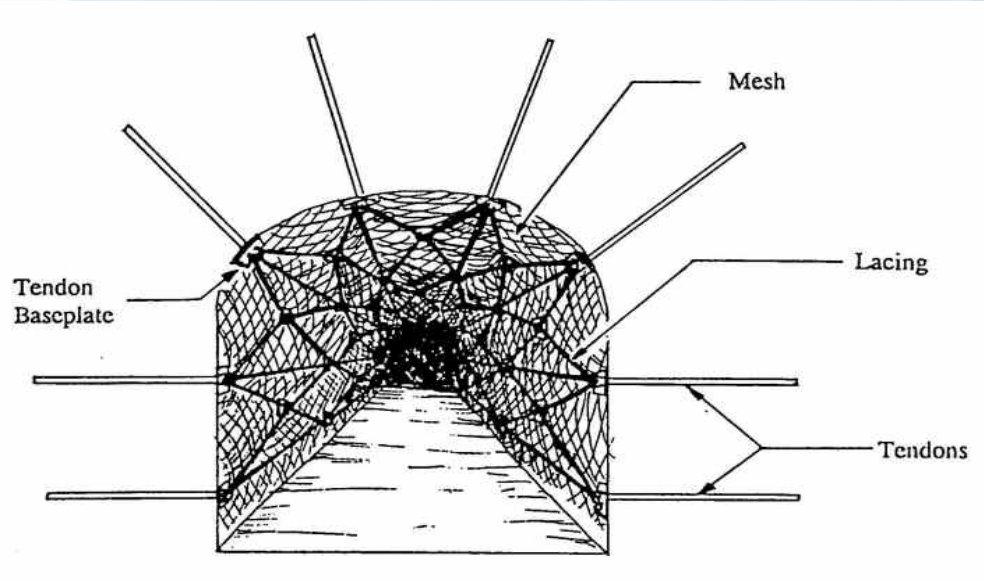
  - FEA model
  - Experimental bolt

- Simulating two mayor resin anchored rock bolts

  - Partially embedded bolts
  - Local corrosion defects

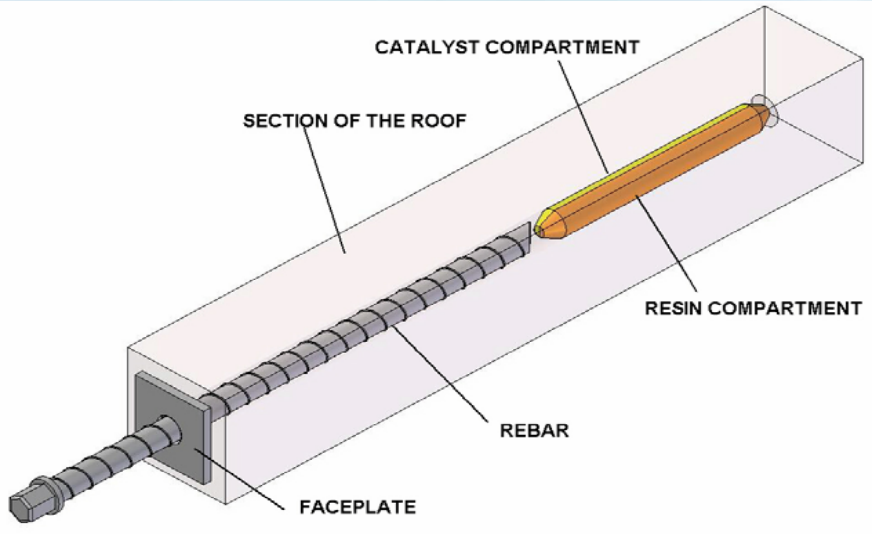
Rock Bolts and their associated Problems

- Rockbolts - steel bolts fixed into the roof to prevent the movement and expansion of rock strata in mines.
- 1087 ground fall accidents were reported in 2006 with 85 people killed in these accidents.



The Resin Anchored Bolt

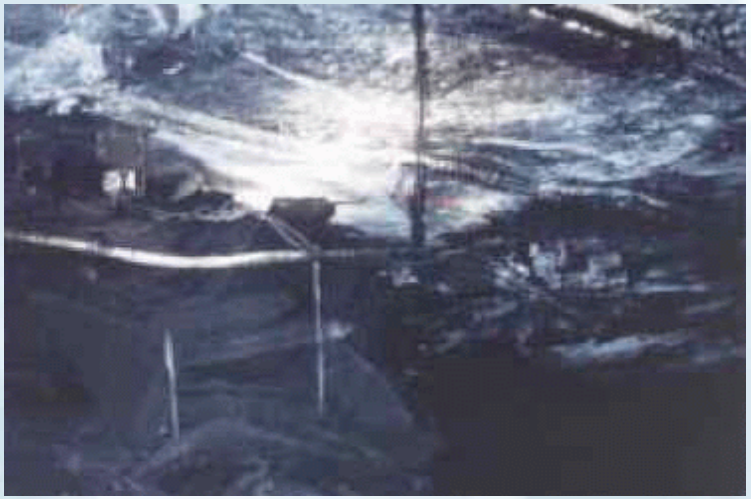
- Different types of rock bolts in used. This study focussed on resin anchored rock bolts.
- More than 16 million rock bolts are installed each year. Of these 45 percent is resin anchored bolts.
- 50 % of the resin bolts installed not effective.
- Two component cartridges containing resin and catalyst.
- Bolt rod spun into the resin cartridges by the drill.



The Resin Anchored Bolt

Different problems with resin anchored rock bolts:

- Incomplete mixing
- Overspinning
- Corrosion
- Voids
- Cracks



All result in a unsatisfactory bond and/or reduction of the integrity of the roof support.

Rock Bolt's Integrity Testing

A few approaches are presently used for measuring integrity.

Pull-Out Test:
Most frequently used in the SA mines.
Very expensive and destructive.

GRANIT (Scotland):
Resultant vibrational response interpreted by neural networks. It is the only non-destructive patent on the market
Very expensive and can only be used on bolts that was monitored when it was installed.

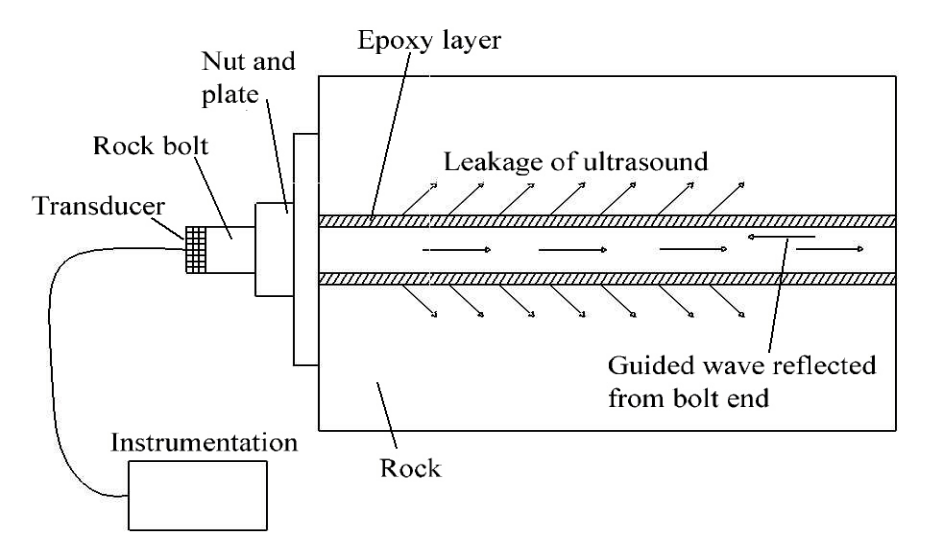
Boltometer (Sweden):
Ultrasonic device, in used since 1979. Can indicate bad grouting, but if the impedances of the grout and surrounding rock are the same, wave energy will dissipate into the rock before it could reach a major defect, signaling good grouting.

Imperial College (UK):
Pulse echo test using guided ultrasonic waves.

Rock Bolt's Integrity Testing

Ultrasonic Guided Waves:

Principle:
A short duration Gaussian windowed sine burst is used to excite a guided wave in the bolt from the free end. The wave is then reflected from the other end and from any major defects.
From the reflection arrival time and knowledge of the wave velocity dispersion curves, the positions of the defects or the bolt length can be calculated.



Rock Bolt's Integrity Testing

Ultrasonic Guided Waves:

- The quality of the grouting and the location of the defect can be determined.
- Specific modes can be selected that are less sensitive to differences in impedance compared to the Boltometer.
- Present study extends the previous work to investigate damage in more realistic embedded bolts which deviate from pure cylinders.

Ultrasonic Guided Waves

What is guided waves?

- Ultrasonic waves that propagate in solid media with boundaries. These ultrasonic waves experience reflection and refraction with the boundary of the solid, which cause mode conversion between longitudinal and shear waves.

- Different guided wave modes can exist in a cylindrical solid (Rock Bolt). Each of these modes has a particular wave structure. The wave structure describes the distribution of particle motion in the cylindrical solid.

- Some modes have large particle motion amplitudes near the surface, while others feature more intense motion near the middle of the cylinder. The wave structure determines the sensitivity of the particular mode to a particular flaw type.

Ultrasonic Guided Waves

- The velocity of propagating waves is one of the most important parameters in ultrasonic testing. In bulk waves it is constant and can be calculated with the well known equation:

  $c^2 = E/p$,

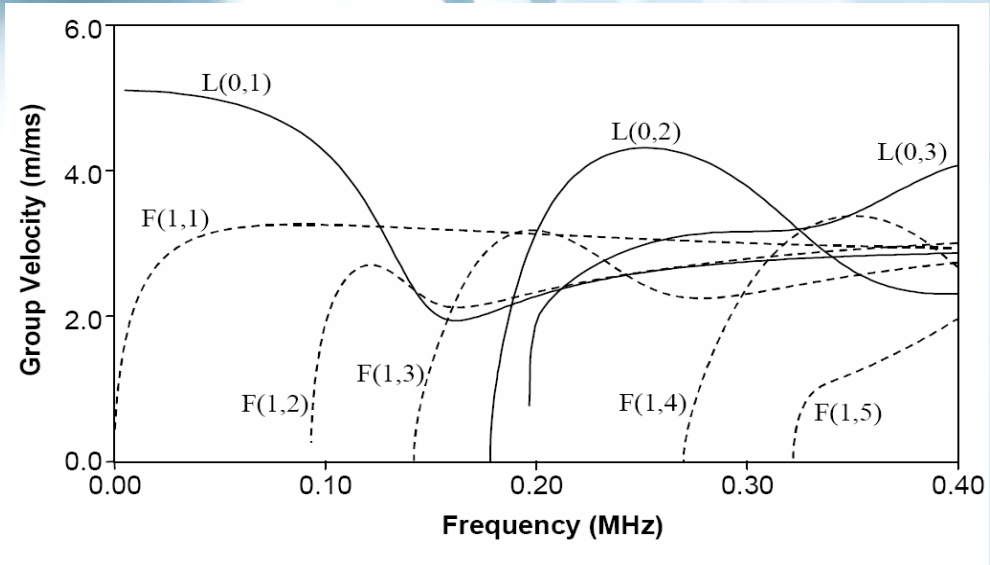
- but in guided waves it changes with frequency and this relationship is represented on a dispersion curve.

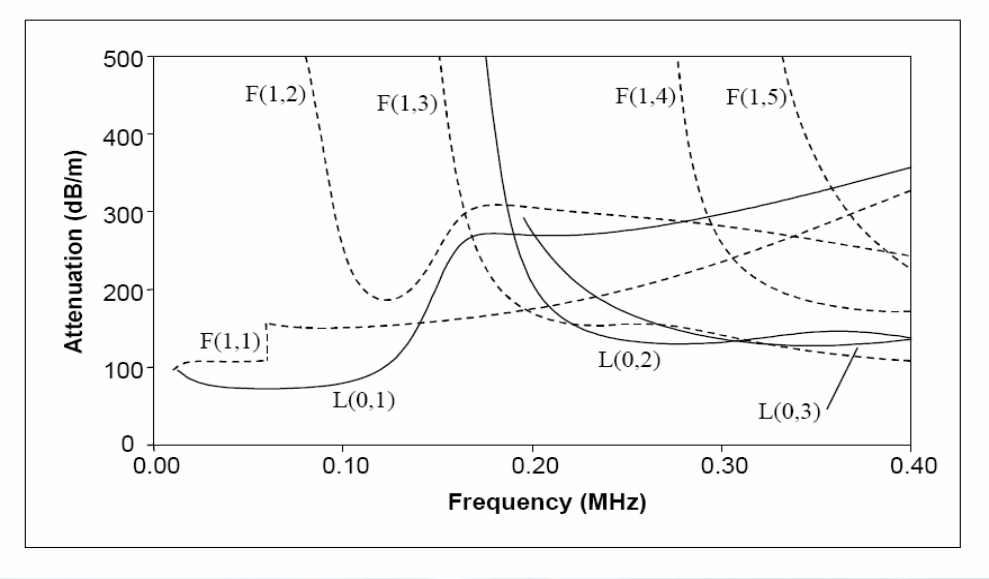
Ultrasonic Guided Waves

- Dispersion curves are used to describe and predict the relationship between frequency, phase velocity and group velocity, mode and thickness.

- An example of the phase and group velocity curves for a 20 mm diameter perfectly elastic rod in a vacuum is shown in the following slide:

Ultrasonic Guided Waves





FEA Modelling of guided waves

Axisymmetrical models.
Assuming axial symmetry of the geometry, load, boundary conditions and materials, allows one to analyze the three dimensional bolt and surrounding rock mass with a two dimensional model.

Full three dimensional models.
Defects can occur that are not symmetric around the axis and in which case a three dimensional model of the rock bolt will be necessary.

Software.
The MSC.Software package, comprising MSC.Patran, MSC.Nastran and MSC.Dytran

Computer Capabilities.
3.2 GHz Pentium 4 computer and 3 GB of RAM.

FEA Modelling of guided waves

The effect of mesh density and time step size:

- The time step size is more critical than the element size for the implicit solver
- The element size is more critical than the time step size for the explicit solver.

FEA Modelling of guided waves

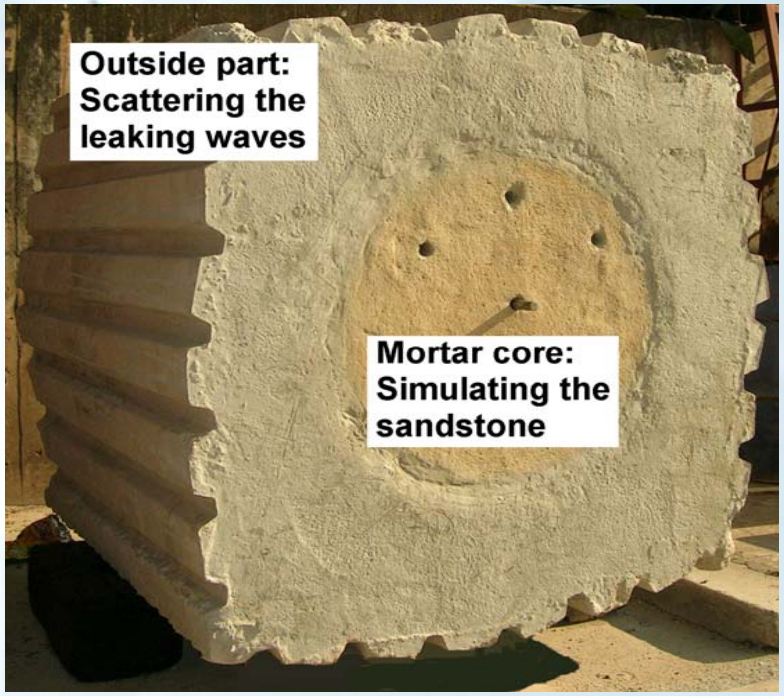
Infinite boundary? Unsolvable FEA model?

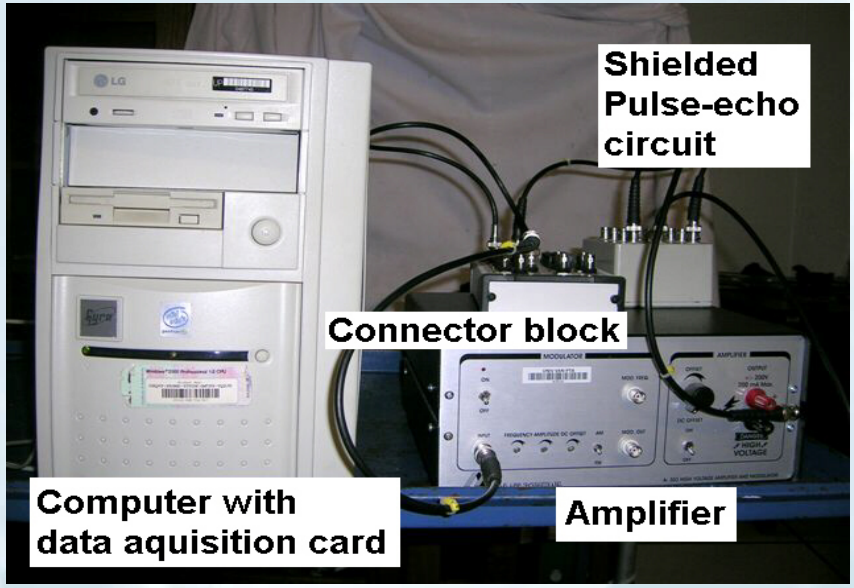
The finite boundary of the rock mass of the FE model causes the leaking waves to be reflected and superimposed on the progressing waves in the bolt.

Solutions:

- Energy absorbing elements at the boundaries.
- Move the boundary a large distance away from the bolt so that the boundary does not influence the results. This however causes the model to become very large and consequently time-consuming to solve, limiting the present study to the low frequency scenario.
- Maybe with a new generation of computers it will also become practically feasible to model the high frequency scenario.

Experimental setup



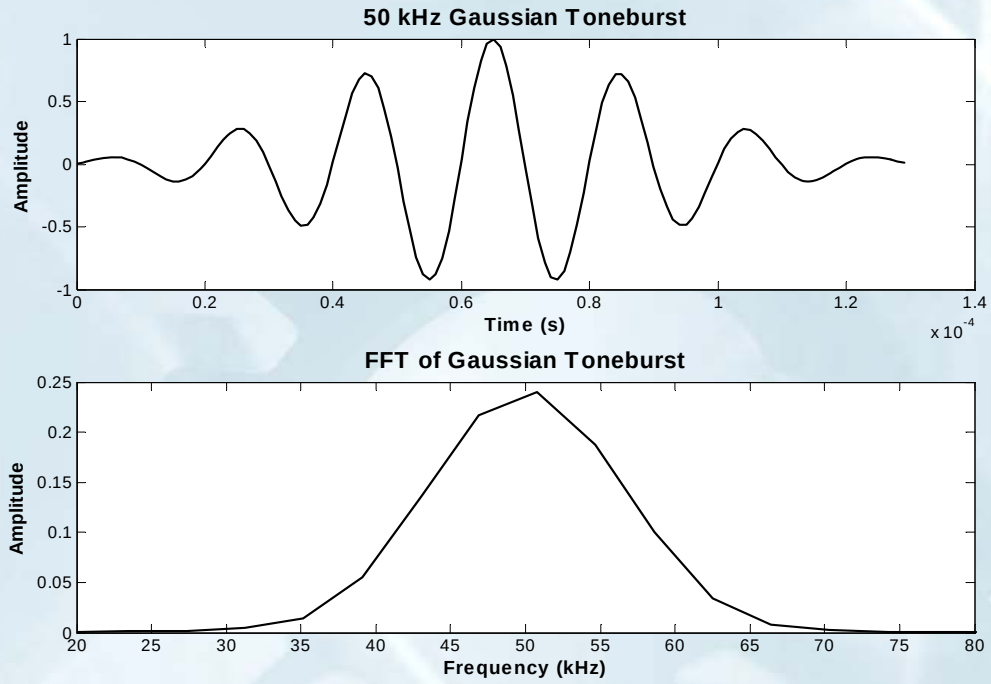


Experimental setup

Exciting a specific guided wave mode.

Signal with a large number of cycles.
- Conceal early reflections.

•Gaussian Windowed sine burst.
The Gaussian window allows more energy to be focussed at a particular frequency.



Experimental setup

Exciting a specific guided wave mode.

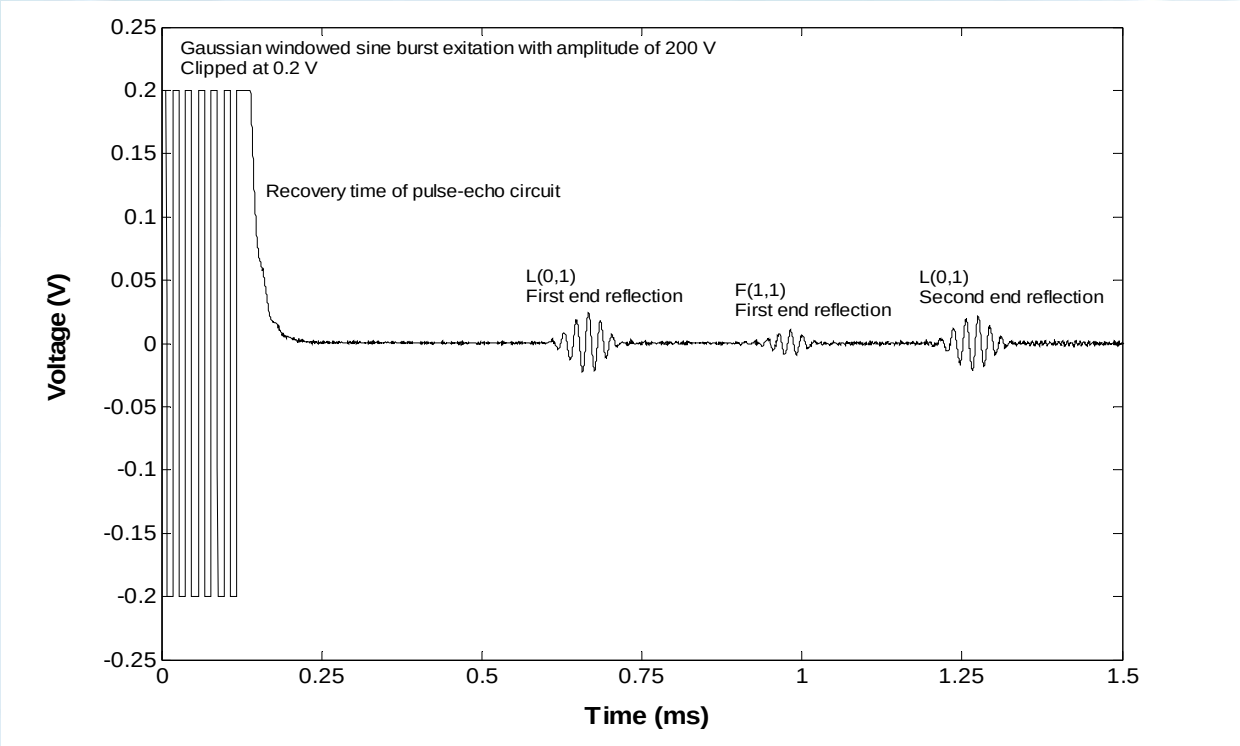
- Displacement of the transducer should match the displacement of the mode profile.

- Piezo ceramic transducer. Disc that was cut with thin blades into small blocks. These blocks can be individually controlled to excite different mode shapes.

Early Investigations

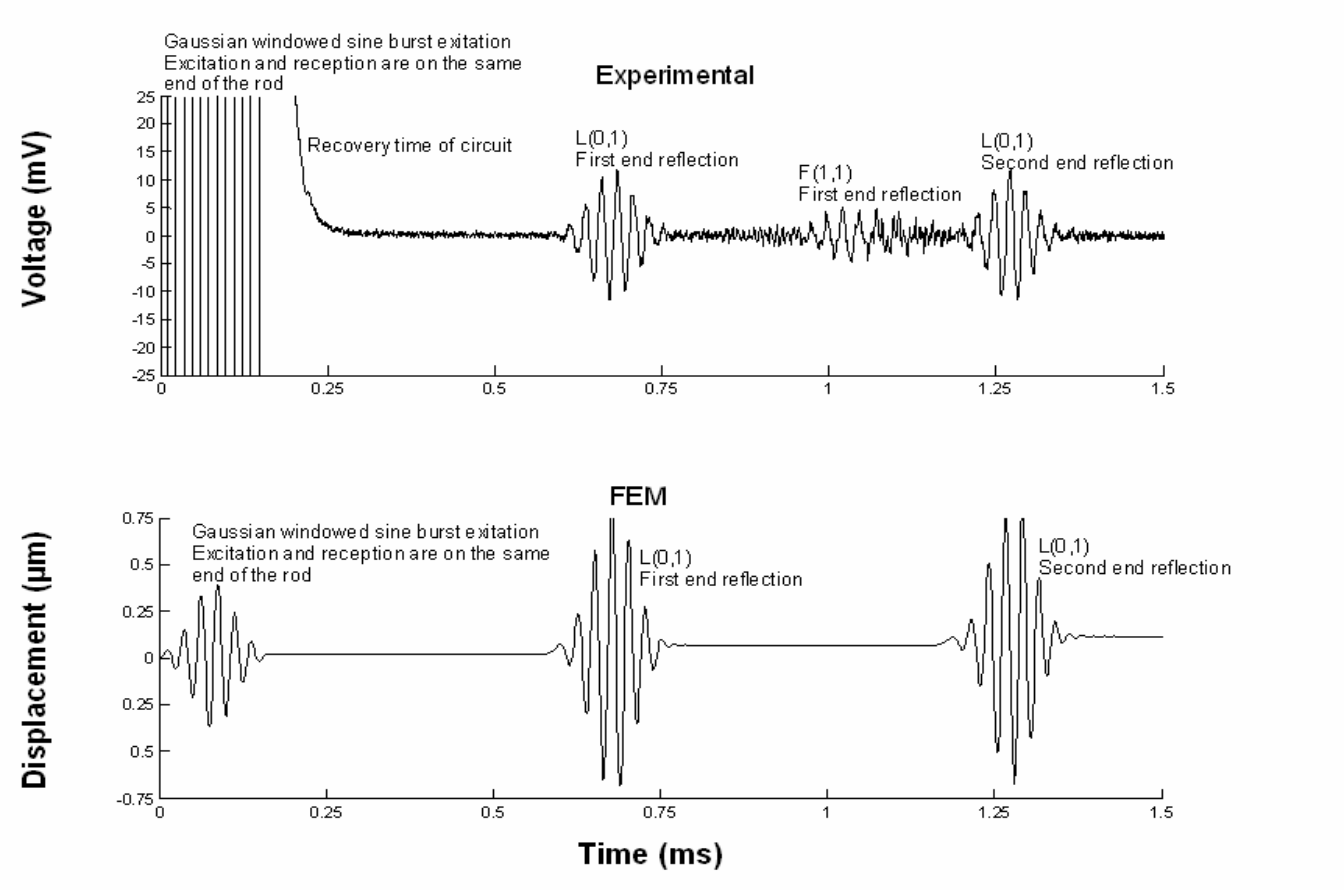
- Experimental Unbounded rock bolt

A 1.5 m long mild steel bolt, with a diameter of 20 mm was suspended in the air on strings to represent an unbounded configuration.



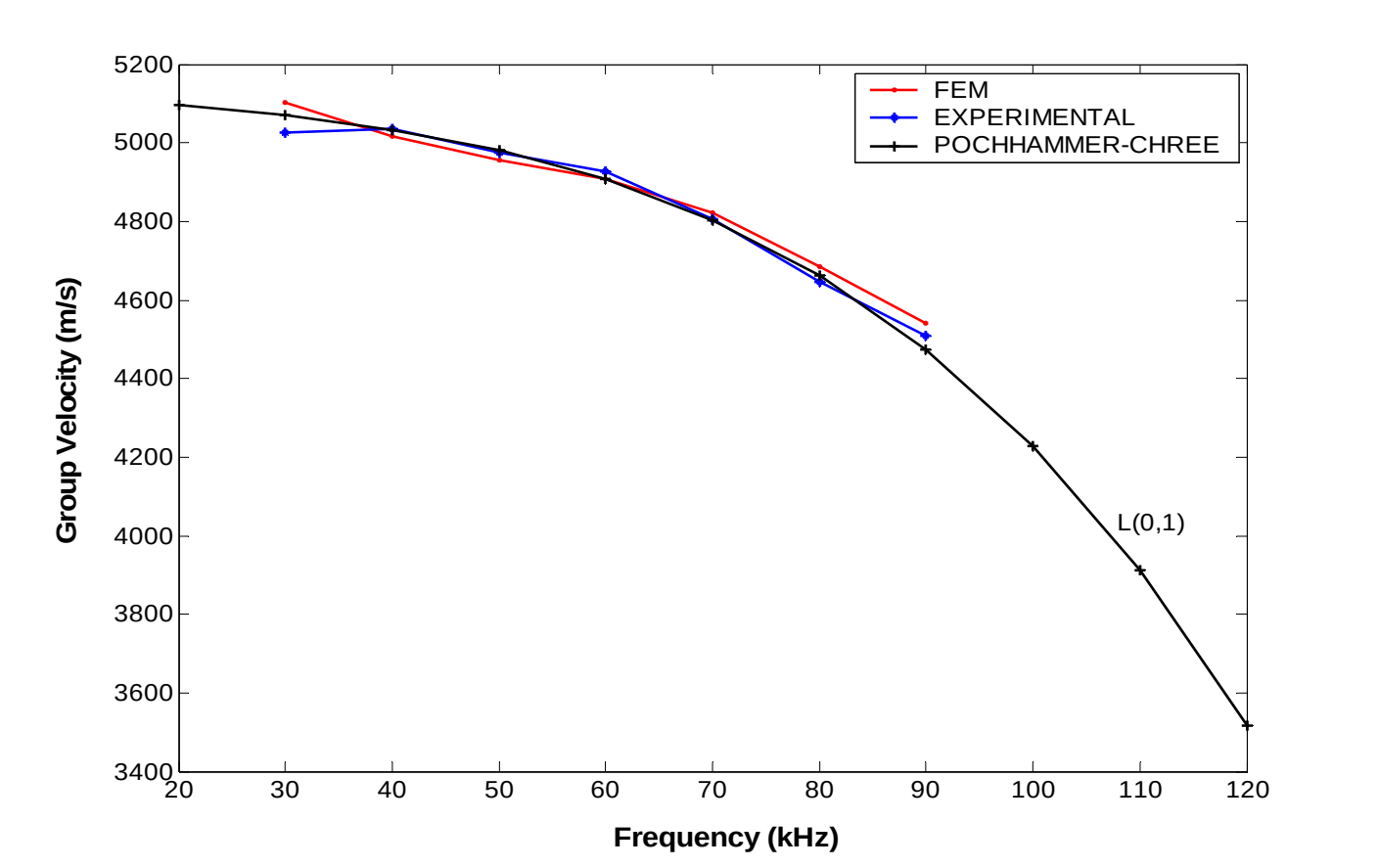
Early Investigations

- Comparison Experimental and FEA



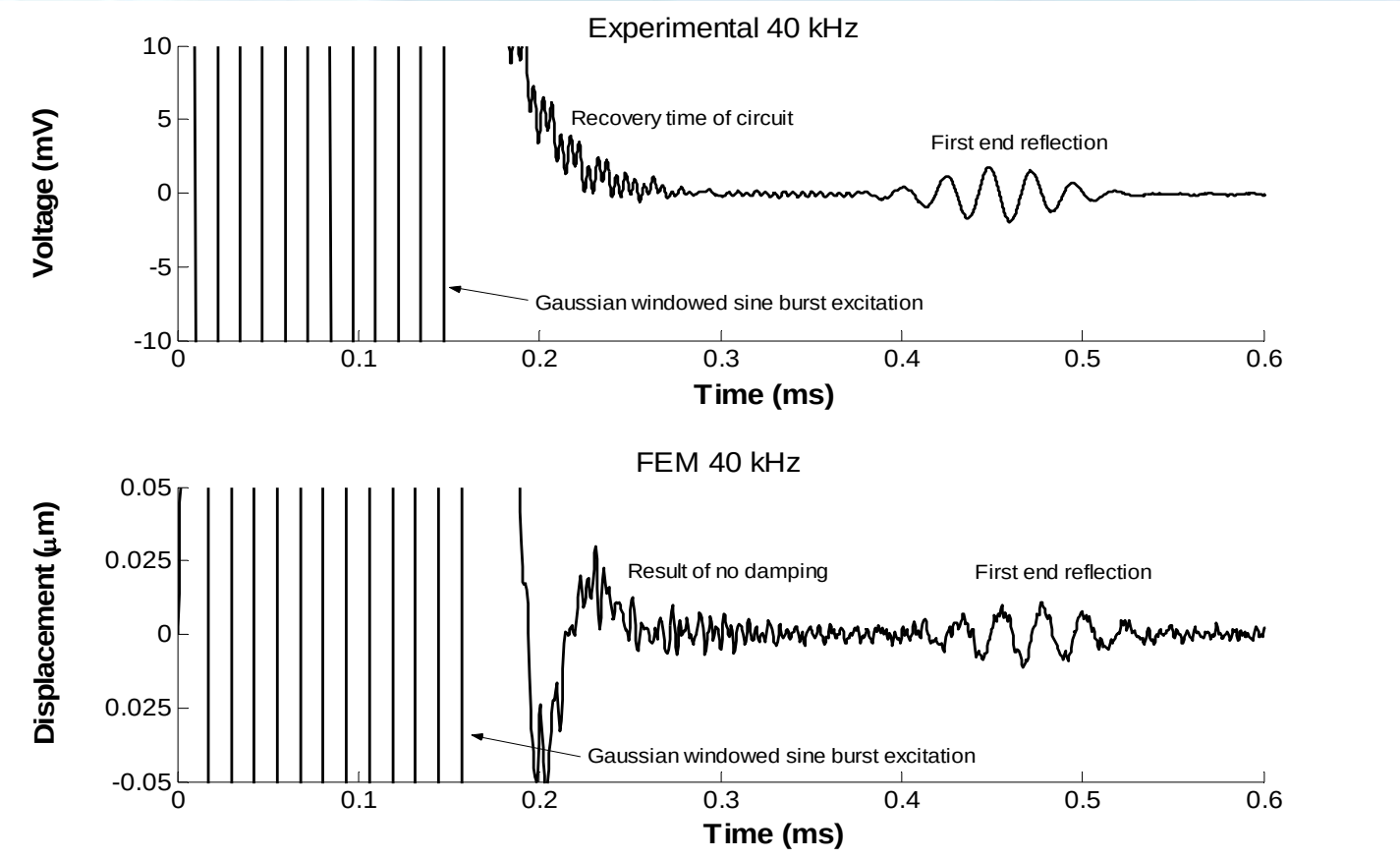
Early Investigations

- Group Velocity Comparison



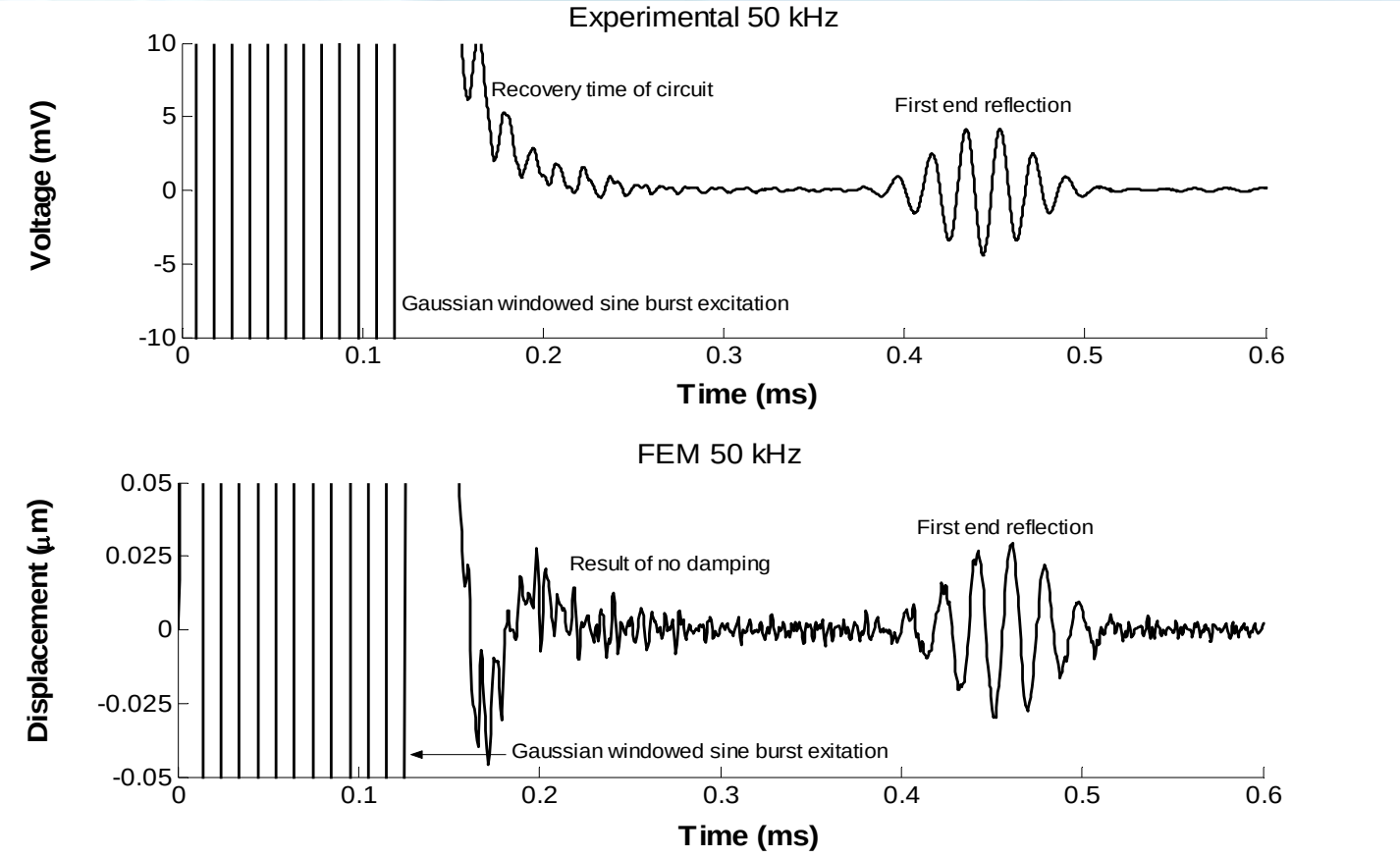
Perfectly Embedded Bolt

- Perfectly Embedded bolt – 40 kHz



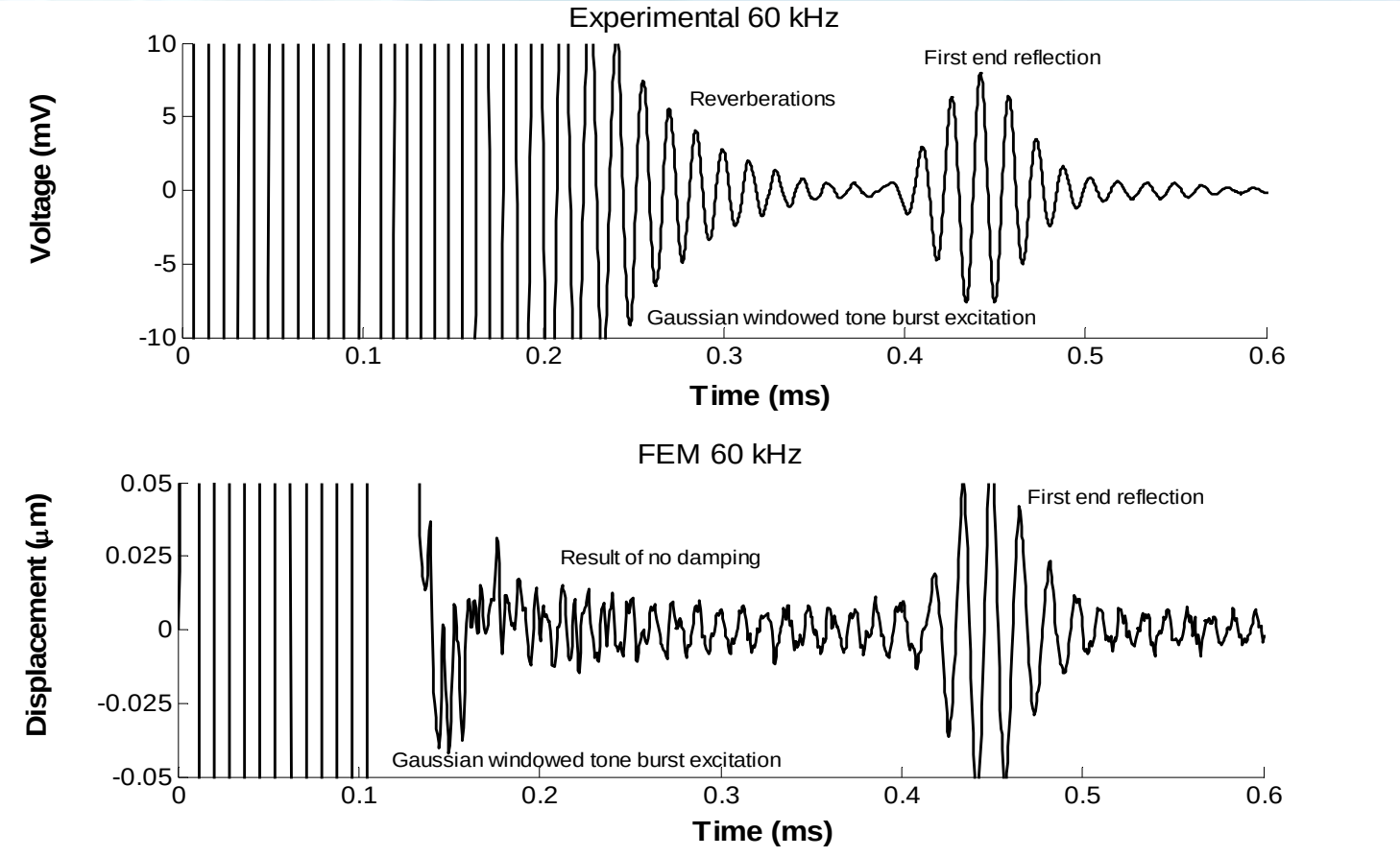
Perfectly Embedded Bolt

- Perfectly Embedded bolt – 50 kHz



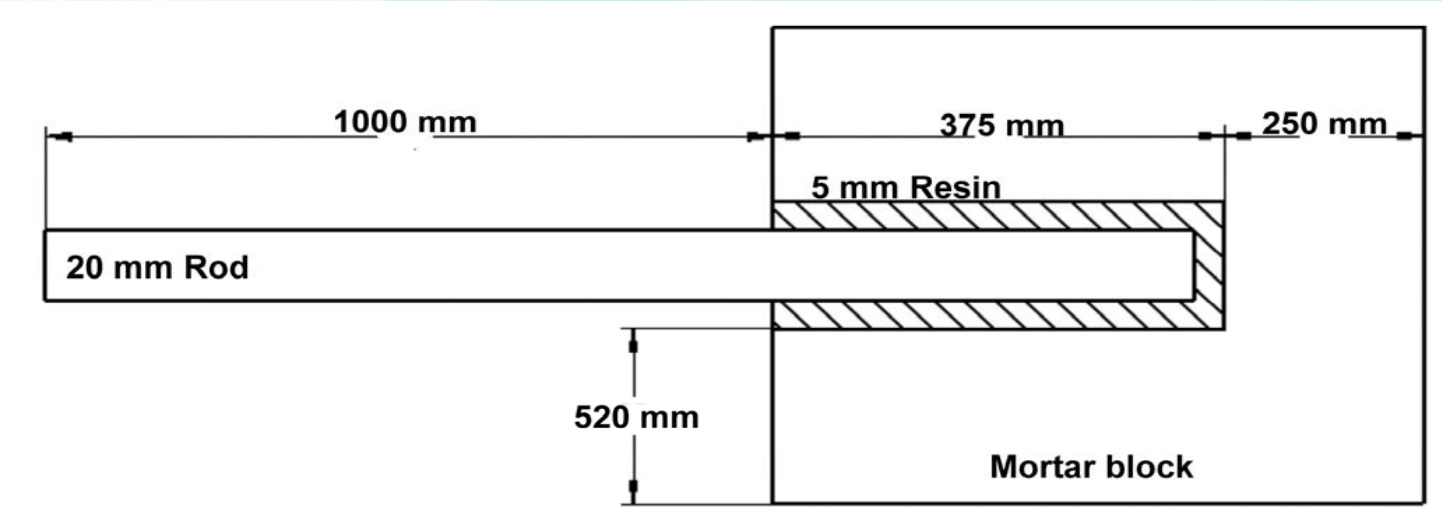
Perfectly Embedded Bolt

- Perfectly Embedded bolt – 60 kHz



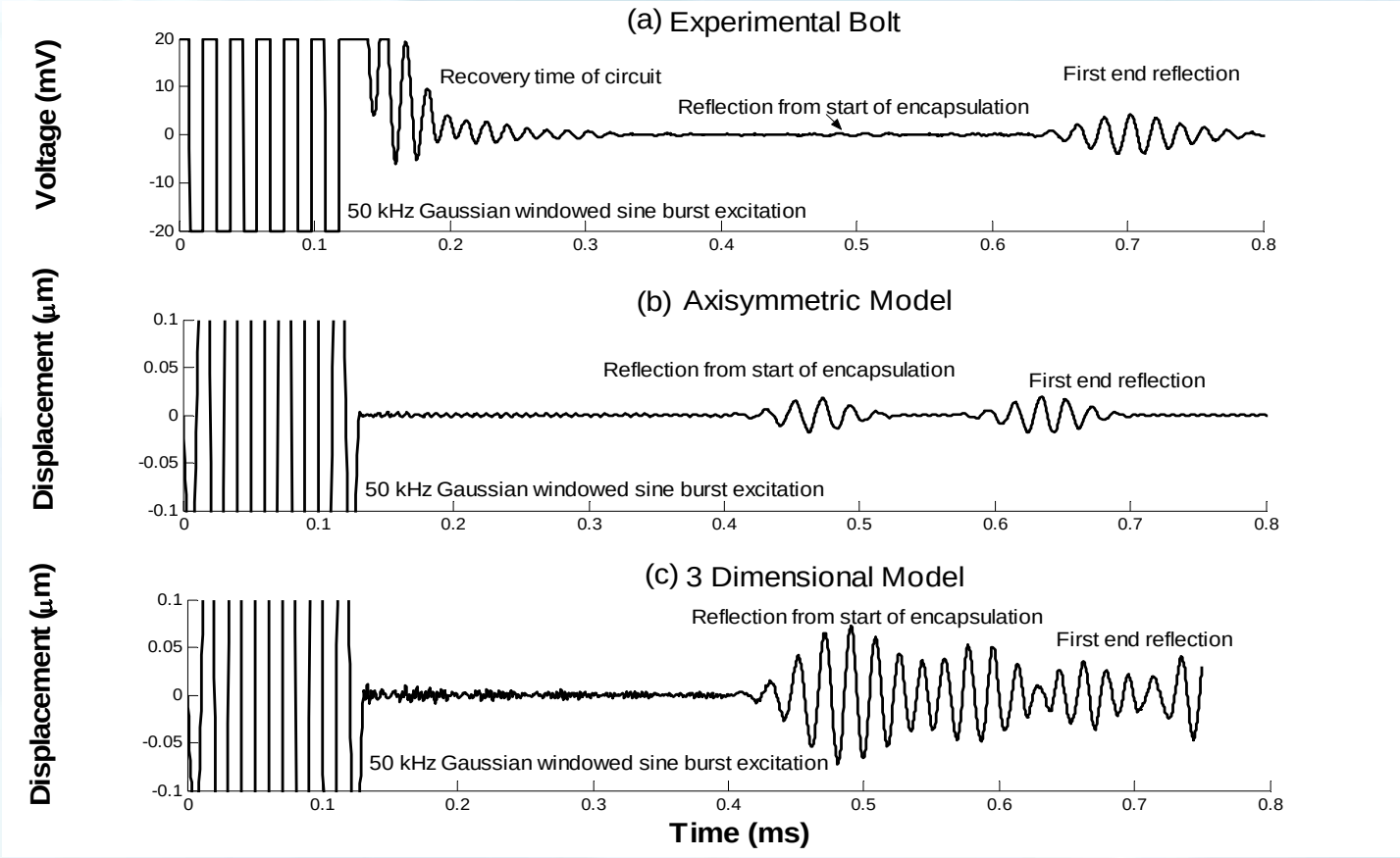
Defect - Partially Encapsulated bolt

- Model of the Partially Encapsulated Bolt



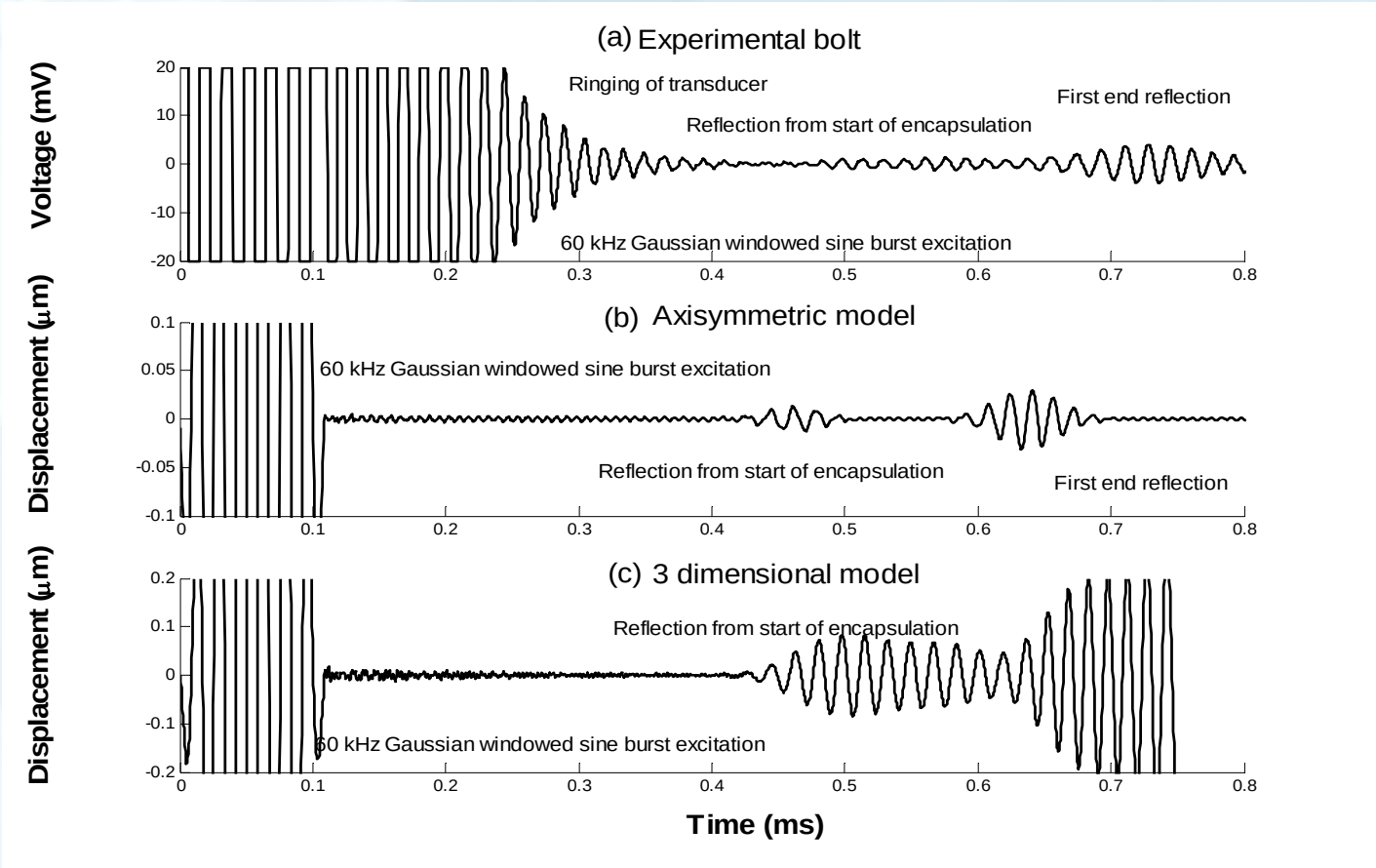
Defect - Partially Encapsulated bolt

- Results - 50 kHz



Defect - Partially Encapsulated bolt

- Results - 60 kHz



Defect - Partially Encapsulated bolt

Concluding Remarks – Partially encapsulated bolts.

- The three dimensional model the reflected signal becomes stretched out in time for the higher frequencies. At higher frequencies the velocity of the pulse in the concrete causes earlier reflections from the boundary of the mortar block. These reflections interfere with the reflection from the start of the encapsulation, causing the stretched signal.

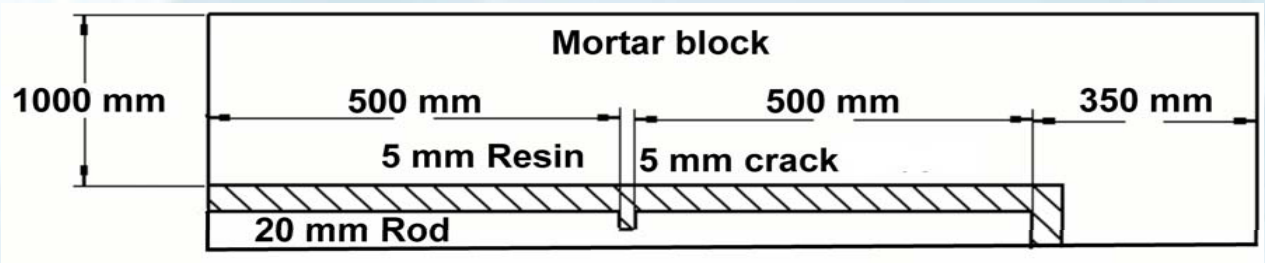
- For the higher frequency excitations the reflections from the start of the encapsulation are smaller than the bolt end reflections. This illustrates that more energy propagates in the centre of the bolt at higher frequencies and more energy propagates near the bolt surface at lower frequencies.

- The start of the encapsulation are much smaller for the experimental bolt. An explanation is that for the experimental bolt more energy is dissipated due to leakage which could not be exactly modelled by the FE models due to uncertainties of the material properties.

- From the above results it is concluded that the signal is not significantly influenced by resin defects when the frequency of the signal is high, because the energy propagates more in the centre of the bolt.

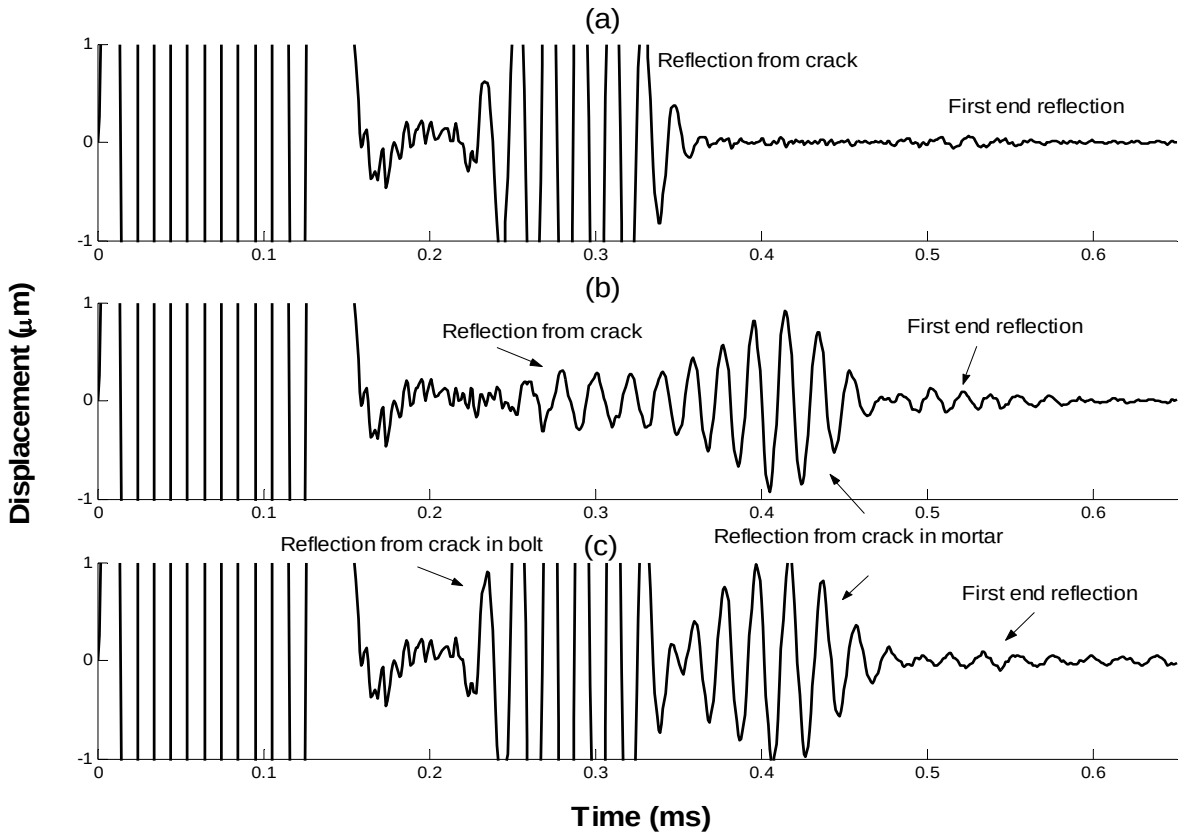
Defect – Local corrosion cracking

- Model of the Corrosion cracking



Defect – Local corrosion cracking

- Results



Defect – Local corrosion cracking

- Concluding Remarks – Local corrosion cracking.
- It is possible to detect simulated local corrosion cracks with the finite element models.
- Clear reflections for the crack in the bolt can be seen. If the bolt, resin and rock are cracked, different reflections are observed. These different reflections complicate the interpretation of the results.
- Overlapping of returning signals can also add to complicate the interpretation of the results. It is therefore recommended that more sophisticated signal processing techniques be utilized for future studies.

Conclusion and Recommendations

- Guided ultrasonic waves testing seems to hold promise as a testing method, as comparable results could be obtained from experimental and finite element models considered in this study.

- <u>Unbounded bolt</u>

  Axisymmetrical model compares well with the experimental bolt. The group velocity curves of these models compared well with the Pochammer-Chree frequency equation group velocity curve for a rod in air.

- <u>Partially encapsulated bolt.</u>

  The FE model of this bolt compares well to the experimental results. At high frequencies the energy propagates more along the centre of the bolt. It is recommended to use lower frequencies when defects such as these need to be identified.

Conclusion and Recommendations

Local corrosion cracking.

- It is possible to detect these simulated local corrosion cracks with the finite element models.
- Clear reflections from the crack in the bolt can be seen. If the bolt, resin and rock are all cracked, different reflections are observed. This complicates the interpretation of results.
- It is recommended that signal processing techniques be investigated in future studies.
- Further investigations should consider other scenarios such as inclined and multiple crack scenarios.

Conclusion and Recommendations

- This study considered only the time of arrival to locate the simulated defects. However, the amplitude of the reflecting signal may also contain information on the nature and location of a defect.

- Effect of damping as well as the effect of transducer mounting on the observed responses.

- Considering higher frequencies - higher frequency modes are less sensitive to material properties, epoxy thickness and surface defects. Obtain a reliable indication of the bolt's length.

- Basic principles and concepts developed here could soon be extended to higher frequencies with a new generation of computers or by applying energy absorbing boundaries.

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