Acoustic Wave Crack Detection: A First Principles Approach

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Abstract: Mechanical segments of the many different infrastructures, such as roadways, bridges, cell-towers, pipelines, building materials (rock, concrete, brick, steel, etc.), are susceptible to cracking failures when exposed to differing environmental conditions that arise in normal usage. Examples of such conditions are: thermal cycling, corrosion, load cycling, and weather, to name a few. Since many cracks occur in locations that are not readily accessible or observable, it is necessary to develop methodologies that can determine the existence and/or location of a crack or cracks indirectly.

This model employs the Structural Mechanics Module of COMSOL Multiphysics, Version 5.2a, a transient solver, and an impulse-load located at one position on a rock mass. The impulse load generates an acoustic wavefront comprising both shear and compression waves propagating through the body of the rock mass. Differential analysis is employed to detect the existence of and the number of cracks.

Keywords: crack-detection, acoustic-impulse-load, Fourier Analysis, Structural Mechanics Module.

1. Introduction

Acoustic wave propagation in a solid material can typically occur as shear and/or compressional wave motion in one or all of the three axial directions. The velocity of propagation for the shear wavefront and the compressional wavefront differ significantly.

In this model, the primary analytical consideration will be the single-point transient displacement (shear wave) of a z-axis point on the upper surface of the model geometry. The upper z-axis point displacement is calculated, both with and without cracks in the upper surface, after the impulse-load has been applied to a relatively small area on the lower surface. The application area is centered on the z-axis on the lower surface, and is located directly below the displaced measurement point.
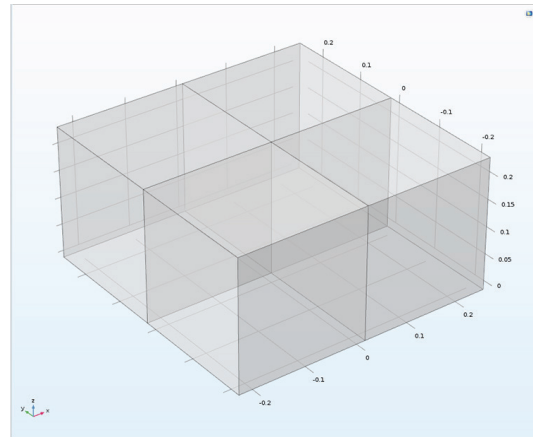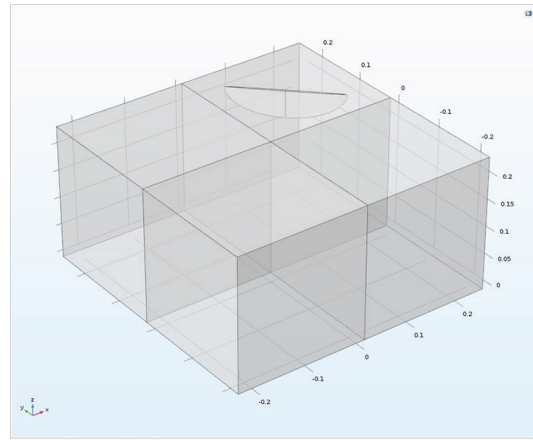

Figure 1. No-Crack Geometry
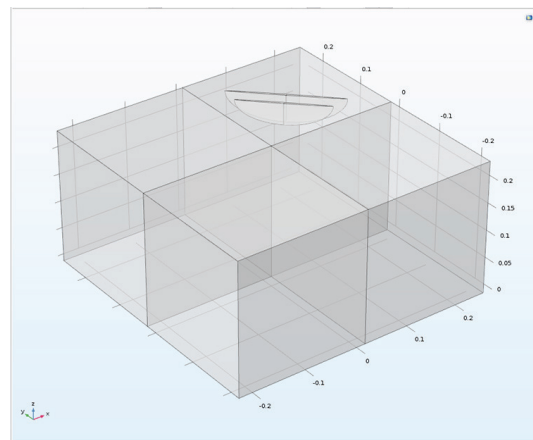

Figure 2. 1-Crack Geometry
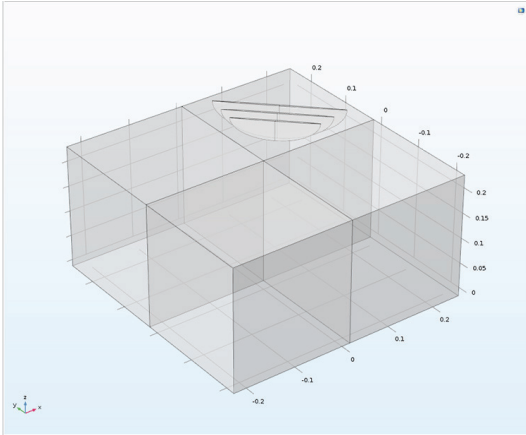

Figure 3. 2-Crack Geometry

Figure 4. 3-Crack Geometry

The No-Crack geometry is shown in Figure 1. Figures 2, 3, and 4 show respectively the 1-Crack, the 2-Crack, and the 3-Crack geometries.

The configuration of each of the imbedded cracks (1, 2, 3) is that of a standard ellipsoidal fatigue crack [1].

2. Crack Detection Assumptions and Methodology

Crack detection is and has been an active field of exploration, both theoretical [2] and applied for a number of years. It is the belief of this author that the concepts presented herein explore a new methodology for the modeling and the detection of cracks and families of cracks in crystalline solids, polycrystalline solids and high viscosity amorphous materials (glasses).

The single fundamental assumption made, in the case of the models presented in this paper, is that the acoustic wave generated in the modeled material (solid), by the impulse load, interacts with the crack/crack family. As a result of the wave-crack interaction, the acoustic wave frequency distribution profile at the displacement point changes.

3. Use of COMSOL Multiphysics® Software

This family of models uses the COMSOL Multiphysics basic module, Version 5.2a, the Structural Mechanics Module, a transient solver, and an impulse-load located at the lower surface center of the rock mass. The impulse-load is located in the exact center of the rock mass on the surface opposite the side of the block that contains the crack(s). The displacement-measurement point is located in the exact center of the surface of the block that contains the crack(s).
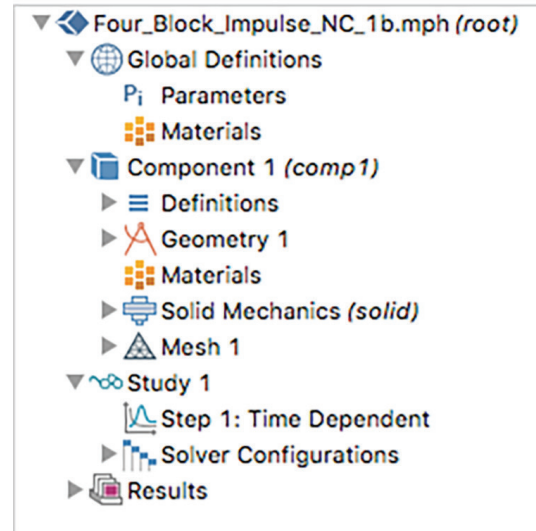

Figure 5. Acoustic Wave Crack Detection Model Tree

Figure 5 shows the Acoustic Wave Crack Detection Model Tree for the No-Crack implementation. This model is derived from the COMSOL Model *Wave Propagation in Rock Under Blast Loads* [3].
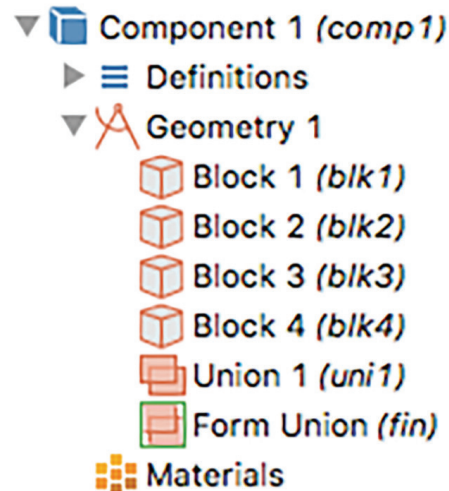

Figure 6. No-Crack Model Geometry

In order to calculate the reference displacement curve shown under the results icon presented in this paper in Figure 5, the No-Crack geometry needs to be built as shown in Figure 6.
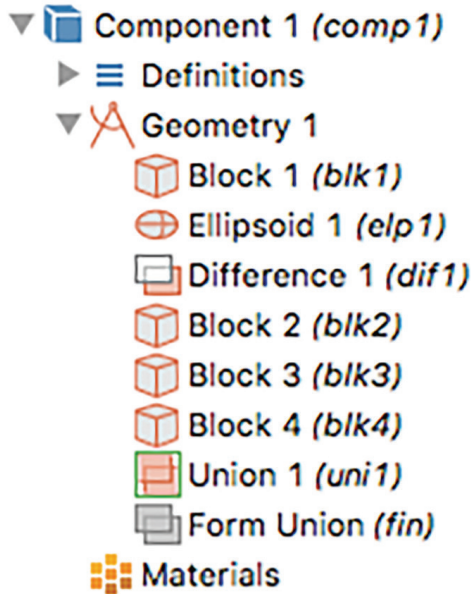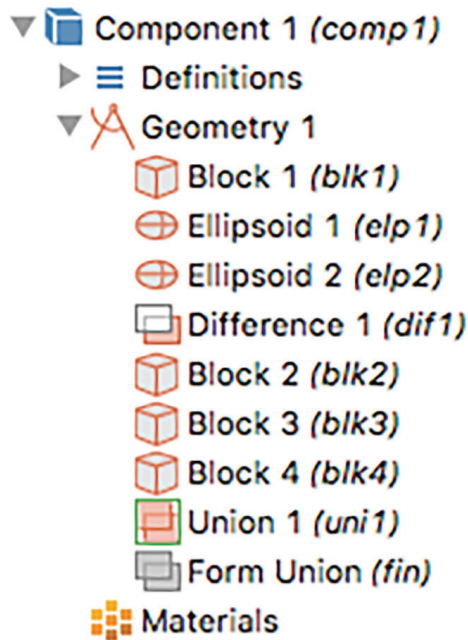

Figure 7. 1-Crack Model Geometry

Figure 8. 2-Crack Model Geometry

In order to calculate the 1-Crack displacement curve shown under the results icon

presented in this paper in Figure 5, the 1-Crack geometry needs to be built as shown in Figure 7.

In order to calculate the 2-Crack displacement curve shown under the results icon presented in this paper in Figure 5, the 2-Crack geometry needs to be built as shown in Figure 8.
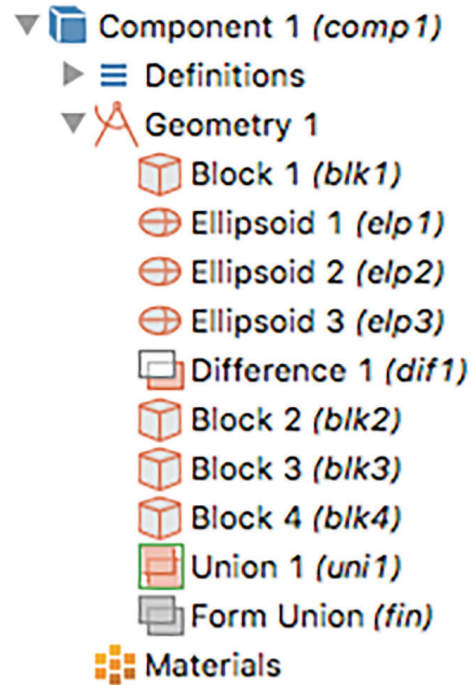

Figure 9. 3-Crack Model Geometry

In order to calculate the 3-Crack displacement curve shown under the results icon presented in this paper in Figure 5, the 3-Crack geometry needs to be built as shown in Figure 9.

The easiest methodology to apply when creating this family of models for use in the subsequent acoustic wave calculations is to first build the No-Crack Model. Then, run the No-Crack Model to verify that no errors or omissions have been made in the process. Once the No-Crack model is completed, make accurate copies of the No-Crack Model, change the name of each saved model, and add the appropriate number of cracks to each copied model, as needed.

4. Expanded Model Builder Tree

Figure 10 shows the expanded Model Builder Tree for the No-Crack Model. There are several items that need to be considered when proceeding with this work. First, be sure that the Parameters file contains all of the dimensional parameters needed to create the geometrical blocks and the impulse-load.
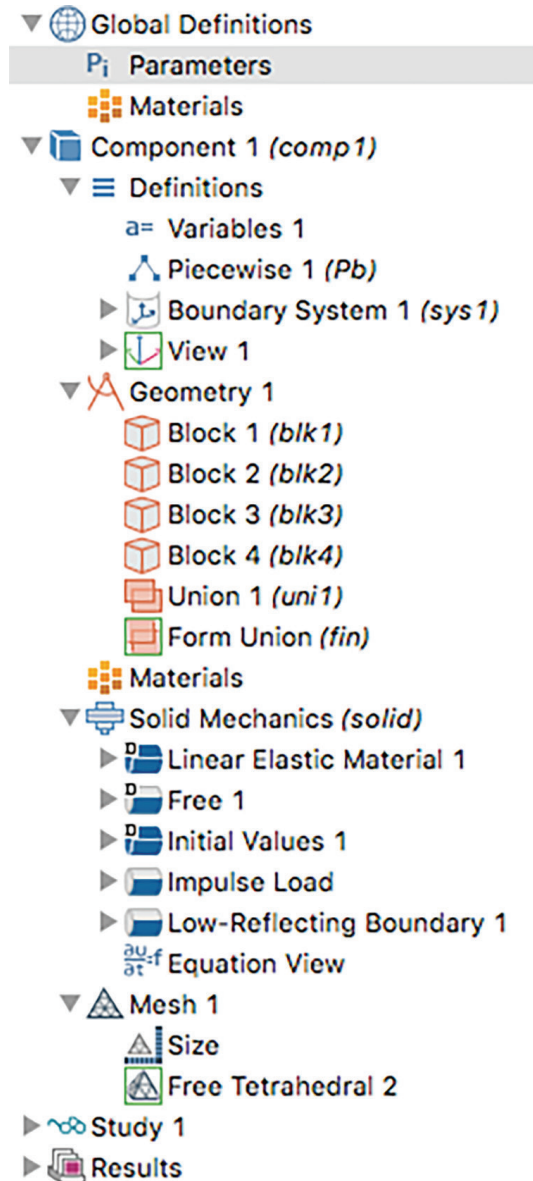

Figure 10. Expanded Model Builder Tree

The Piecewise function is the pressure function of the impulse-load. The variables function defines the area over which the impulse-load is applied. The details of each Function and the associated formulas are available in the step-by-step instructions in reference 3.

When adding the cracks to the No-Crack geometry, be sure to build the cracks as shown in Figures 7, 8 and 9.

In the Solid Mechanics (solid) module, in the Linear Elastic Material 1 interface, enter the parameters for Young's modulus, Poisson's ratio and the Density. Create a Boundary Load interface and rename it "Impulse Load". Enter the Impulse Load function parameter. Create a Boundary Load interface and rename it "Low-Reflecting Boundary 1". Select all of the vertical sides (8) of the final block.
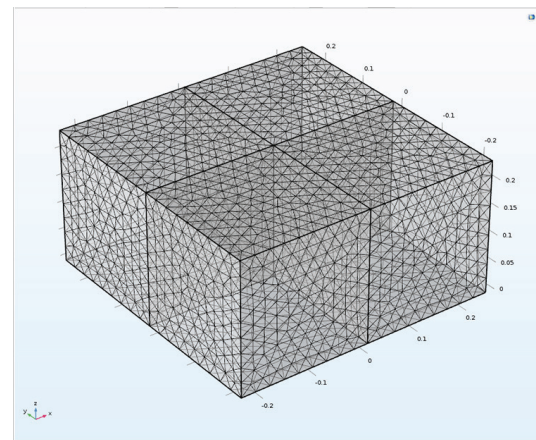
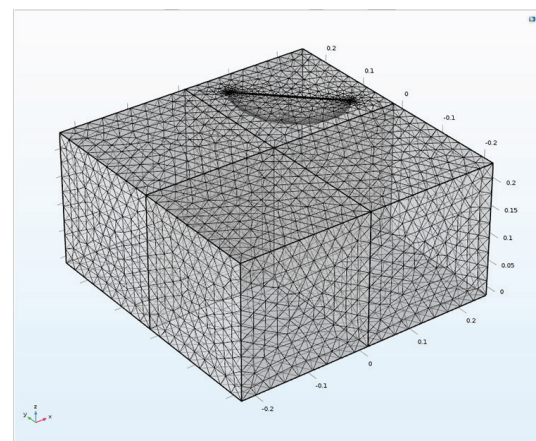## 5. Meshed Geometries

Figure 11. No-Crack Meshed Geometry
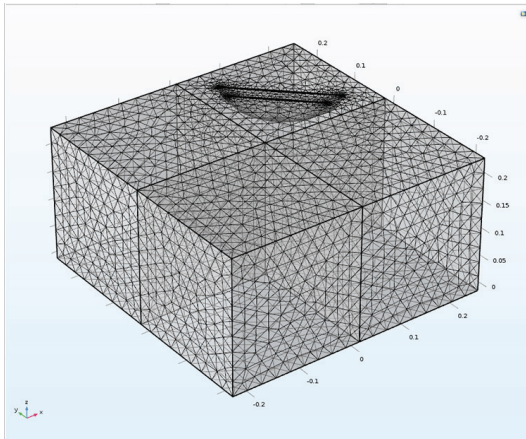

Figure 12. 1-Crack Meshed Geometry

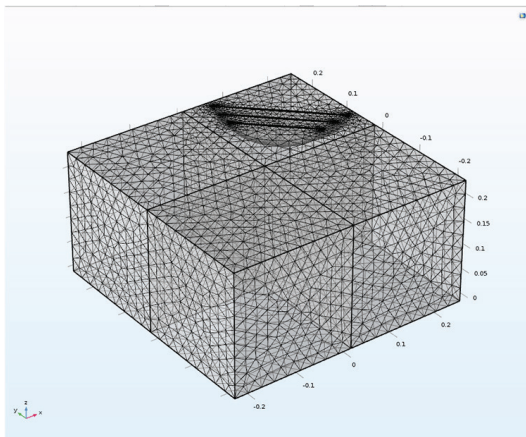**Figure 13.** 2-Crack Meshed Geometry

Figure 14. 3-Crack Meshed Geometry

The mesh used in each of these models is a Free Tetrahedral, General Physics, Finer mesh.

The No-Crack Geometry Mesh is shown in Figure 11.

Figures 12, 13, and 14 show respectively the 1-Crack Mesh, the 2-Crack Mesh, and the 3-Crack Meshed geometries.

6. Calculated Results

Figure 15 shows the Model Tree with the Results section expanded. The Study, for each model, calculates the displacement of the measurement point for a $4.0E^{-4}$ second response period.
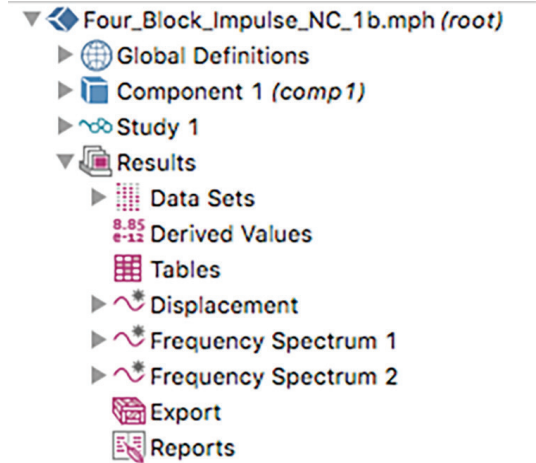

Figure 15. Expanded Results Model Tree

The Displacement Curve for the No-Crack Geometry (Reference Curve) is shown in Figure 16.
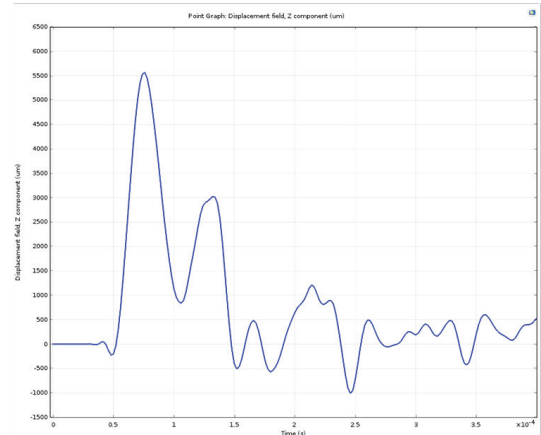

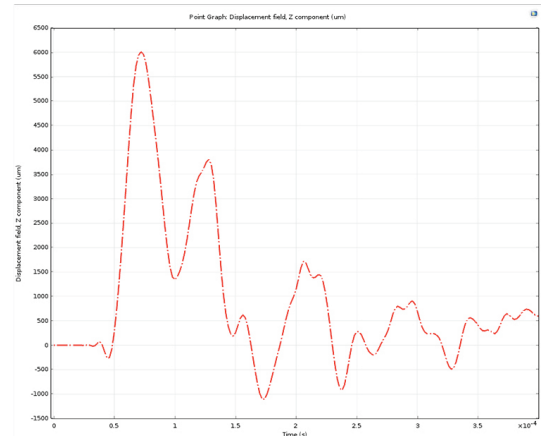**Figure 16.** No-Crack Displacement Curve

Figure 17. 1-Crack Displacement Curve

The Displacement Curve for the 1-Crack Geometry is shown in Figure 17.

The difference between the cracked geometries response curves and the un-cracked geometry response curve, is easily determined by using differential analysis, after the submission of the Displacement curves to Fourier Analysis.
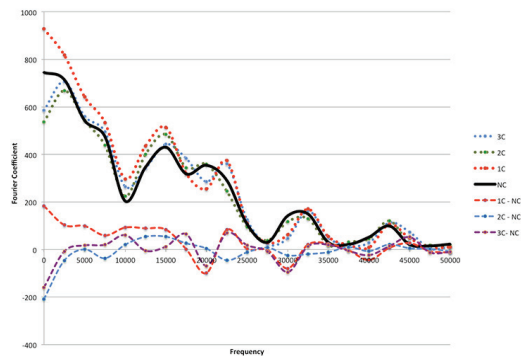

Figure 18. Differential Crack Detection

Figure 18 shows the collected results of all four models and the differential analysis. The upper four curves are the curves before differential Fourier Analysis. The lower three curves show the 1-crack, 2-Crack, and 3-Crack difference curves.

8. Conclusions

Figure 18 shows that the presence of 1 or more cracks in the geometry significantly alter the frequency spectrum of the displacement curve.

9. References

1. M.D. Richards, J.D. McColskey and T.S. Weeks, *Fatigue Flaw NDE Reference Standard Development Phase I-Feasibility Study*, NISTIR 7902, http://dx.doi.org/10.6028/NIST.IR.7902
2. D.N. Alleyne and P. Cawley, *The Interaction of Lamb Waves with Defects*, IEEE Trans. On Ultrasonics, Ferroelec. And Freq. Cont., **Vol. 39, #3,** pp.381 (1992)
3. COMSOL Multiphysics Model 12811.