# DYNAMIC COUPLED STRUCTURAL-ACOUSTIC-PIEZOELECTRIC FINITE ELEMENT ANALYSIS OF A LAYERED 1-3 COMPOSITE, HALF-WAVELENGTH RESONATOR UNDERWATER TRANSDUCER ARRAY

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## Abstract

The coupled structural, acoustic and piezoelectric noise propagation physics within a layered 1-3 piezocomposite, half-wavelength resonator transducer array for high-frequency, broadband underwater applications is modeled herein using dynamic Finite Element Analysis (FEA). This analysis is being performed primarily to evaluate the complex steady-state dynamic response of the multiple-layered composite array in order to ensure bond structural integrity during high-frequency operation. Specifically, various geometric configurations of the individual array layers can now be examined to determine their effect on both array performance and structural integrity (e.g., relative PZT element spacing between layers, bond materials, joining layer thickness). The results of the present analysis have also been compared to experimental data being collected on prototype layered 1-3 piezocomposite arrays.

## 1-3 COMPOSITE ½-λ RESONATOR TRANSDUCER ARRAY

### Detailed Description of Layered Transducer Array Element.

Recent research at the Naval Undersea Warfare Center Division (NUWC), Newport, RI, USA, has focused on the use of 1-3 piezocomposites for the electro-mechanical coupling component of an underwater transducer array element. Figure 1 shows a photograph of a prototype 1-3 piezocomposite half-wavelength transducer element. As shown in the figure, the array element is comprised of two 1-3 composite PZT element layers (each with an upper and lower copper electrode coating) separated by a layer of mechanically isolative alumina.

Both the outer and inner electrode layer pairs are electrically wired together and the array element functions in a half axial wavelength manner about the center alumina layer. That is, the axial displacement is a maximum at the outer faces of the upper and lower 1-3 composite layers and theoretically zero at the alumina layer.

A Syntech backing material, shown in gray in Figure 1, is mounted to the lower side of the two layer 1-3 composite system primarily to spread out the array transmissibility Q. Not shown in Figure 1 is a urethane acoustic window layer that is bonded to the upper (i.e., outer) electrode face which is exposed to the marine acoustic environment.

Lastly, as can be seen in Figure 1, each of the two 1-3 composite coupling layers is constructed as a checkerboard-like pattern of individual 1-3 oriented, square cross sectioned PZT columns (or ”cells”) that extend completely through the full thickness of the layer. These PZT columns are imbedded in a syntactic foam back fill material to form the 1-3 composite layer.

### Fully-Populated Array Operation.

A fully populated array consisting of many of these individual transducer elements may then be assembled and operated both as a projector and as a hydrophone. In virtually the same manner as a standard Tonpilz transducer element array, the 1-3 composite array functions as a projector through application of a voltage potential across the outer and inner electrode pairs causing mechanical strain and resulting acoustic wave propagation. On the other hand, for hydrophone operation, an incoming acoustic wave induces a mechanical strain and thus voltage potential across the calibrated 1-3 composite layers. The main advantages of 1-3 piezocomposite transduction over conventional transduction are primarily the ability to lower acoustic impedance, optimize the electromechanical coupling factor, and the ability to construct conformal arrays over complex curved marine hull shapes.

### Structural Delamination Issues.

One of the main motivations for the present modeling effort was structural delamination which was witnessed between the 1-3 piezocomposite layers and the center alumina layer following extended transducer array operation of a NUWC prototype array. During both high power and long duration array operation experiments, the array acoustic performance abruptly decreased. Post test inspection revealed the presence of delamination failures occurring between the array’s interior bonded layers.

A number of theories for the cause of the delamination failure were examined including bond failure due to excessive heating, bond failure due to structural failure, edge effects, etc. In an effort to examine the culpability of excessive structural dynamics loading in the delamination failure, the coupled numerical modeling effort reported herein was performed.

## COUPLED DYNAMIC FEA MODELING

### Modeling Approach/Goals.

The overall goal of the present modeling effort is to simulate the coupled structural-acoustic-piezoelectric behavior and performance of a 1-3 composite-based transducer array system in an attempt to predict the detailed structural integrity of the overall laminate. Additionally, the validated modeling tool may subsequently be used as a design tool for optimized array element design (e.g., determination of optimal layer thicknesses, number of PZT cell elements, material specifications, etc.). Finally, use of the modeling tool to help gain physical insight into general layered transducer array operation is also a goal of this approach.

### Governing Equations of Coupled Analysis.

The governing linear coupled structural-acoustic-piezoelectric equations of the present work, expressed in matrix form, are:

<u>Structural Equations of Motion</u>:

$$(\mathbf{K} + j\omega\mathbf{C} - \omega^2\mathbf{M})\ \mathbf{u} = \mathbf{F_s} \qquad (1)$$

where $\mathbf{K}$, $\mathbf{C}$, and $\mathbf{M}$ are the complex stiffness, damping and mass matrices, respectively, $\mathbf{u}$ is the nodal displacements vector, and $\mathbf{F_s}$ is the applied nodal forces vector;

Piezoelectric Stress Equations of Motion:

$$\boldsymbol{\sigma} = \mathbf{C}\ \varepsilon - \mathbf{e}\ \mathbf{E} \tag{2a}$$
$$\mathbf{q} = \mathbf{e^*}\ \varepsilon + \mathbf{D}\ \mathbf{E} \tag{2b}$$

where $\sigma$ and $\varepsilon$ are the mechanical stress and strain vectors, respectively, $\mathbf{e}$ and $\mathbf{e^*}$ are the electromechanical coupling matrices, $\mathbf{E}$ is the electric displacement vector, and $\mathbf{D}$ is the dielectric matrix;

Acoustic Equations of Motion:

$$(\mathbf{H} + j\omega\mathbf{D} - \omega^2\mathbf{Q})\ \mathbf{p} = \mathbf{F_f} \tag{3}$$

where $\mathbf{H}$, $\mathbf{D}$, and $\mathbf{Q}$ are the complex inertial, damping and compressibility matrices, respectively, $\mathbf{p}$ is the nodal pressures vector, and $\mathbf{F_f}$ is the applied nodal forces vector.

## 2D Coupled FEA Model of 1-3 Composite Transducer Element.

***A. Single PZT Cell FEA Model.*** The coupled equations of structural, acoustic, and piezoelectric behavior in Equations (1) – (3) are contained in the ABAQUS Standard (v6.5) general purpose Finite Element Analysis (FEA) program distributed by HKS, Inc., used in the current modeling effort. To begin the coupled modeling work, an FEA model of a single PZT "cell" was developed as shown in Figure 2. This "cell" model consists of a single 1-3 composite stack (white region in Figure 2), the syntactic foam backfill material (blue region in Figure 2), an acoustic window layer (green region in Figure 2), and an electrode layer on either end of the 1-3 composite stack. Not shown in Figure 2 is a semi-infinite acoustic region above the window layer that is coupled to it using interface FEA elements.

Numerous static, modal, and steady state dynamic canonical test cases exercising this model were performed in order to prove the feasibility and accuracy of the coupled modeling approach. Some examples included (a) applying an input voltage potential across the electrodes (open circuit case) and examining the resulting mechanical strain of the cell and the acoustic propagation (in the dynamic case), (b) applying a current between the electrodes (closed circuit), and (c) applying an acoustic pressure to the window material (either via an incoming wave or an applied pressure) to get a mechanical strain and examining the resulting electrical response of the 1-3 composite material. In all cases, the displacement of the cell bottom nodes was constrained to zero to simulate the effect of the alumina layer in the full 1-3 piezocomposite transducer element. In the interest of space, Figures 3a and 3b show contour plots of only a few examples of the numerous static and modal test cases, respectively, performed on the single cell model.

***B. Full Two-Layer/16 PZT Cell Transducer Element FEA Model***. Once the single PZT cell canonical test case runs were complete and verified, full two-layer multi-cell FEA models were assembled that simulated operation of a 1-3 piezocomposite transducer element. A series of multi-cell layered models were developed ranging from a two PZT cell model all the way up to a two-layer/16 PZT cell model representing an actual transducer element. As with the single PZT cell model, each of these assembled models were exercised with a series of static, modal, and steady-state dynamic canonical test runs to verify that the correct physical response was being obtained by the model (see, for example, the FEA mesh and static/modal sample results shown in Figures 4a and 4b, respectively, for a two-layer/8 PZT cell FEA model).

Figure 5 shows a full two-layer/16 PZT cell transducer element FEA mesh and accompanying structural boundary conditions for what herein will be called the "simply-supported" baseline case (i.e., simply-supported displacement constraints are applied at either end of the interior alumina layer – with the rest of the model mechanically unconstrained). Also note from Figure 5 that the electrode pair in the interior of the transducer element (adjacent to the alumina layer) is electrically grounded and the outer electrode voltage is allowed to vary as required (or when the voltage is specified as when simulating projector-type array operation).

## STEADY-STATE DYNAMIC NUMERICAL RESULTS

Although the overall scope of the FEA modeling work being reported in this paper examined extensive simulation of many facets of both the projector and hydrophone operation of the transducer array, due to space limitations only a specific example of the projector-based simulation runs is now described.

### Case 1: Simply Supported Boundary Conditions.

For Case #1, an applied AC voltage was applied to the outer electrodes of the “simply-supported” two-layer/16 PZT Cell transducer element FEA mesh shown in Figure 4. Both the resulting structural response of the layered array and the acoustic response in the fluid medium were then determined. Figures 6a and 6b show contour plots of the steady-state dynamic input voltage potential and resulting mechanical displacement, respectively. Figure 7 shows the maximum harmonic Von Mises stress response for this load condition. Note the very high localized stresses in and around the interior alumina layer in the vicinity of the model edges.

It is theorized that these high local stresses result from flexural response of the alumina layer near the edges due to longitudinal-lateral coupling resulting from the “free” edge boundary conditions above and below the alumina layer. That is, the lateral (specifically, sideways) displacement of the upper and lower 1-3 piezocomposite layers arising due to the Poisson’s effect from the longitudinal (or axial) displacement of those layers results in a large bending moment in the alumina layer, particularly near the model edges. It is also theorized that this alumina plate bending is the potential cause of the observed array delamination.

### Case 2: “Sliding Press Fit” Boundary Conditions.

In an attempt to limit the lateral-longitudinal coupling observed in the “simply-supported” Case #1 above, a second FEA model was developed with what will be called “sliding press fit” displacement constraints. Specifically, in addition to the displacement constraints applied in Case #1, the lateral (or longitudinal) displacements of all of the left and right edge nodes are constrained (to give the “press fit” condition) while these nodes are free to displace axially (hence, the “sliding” condition). It is believed that the elimination of the lateral motion at the edges will alleviate the high bending in the alumina, and thus significantly lower the stresses.

Figure 8 shows the maximum harmonic Von Mises stress response for this “sliding press fit” load condition where it is clearly observed that indeed there is significantly reduced flexure and thus stresses in and around the interior alumina layer in the vicinity of the model outside edges. This observation was backed up by numerous additional modeling runs that are not shown herein. Thus, it is concluded that structural integrity of the 1-3 piezocomposite transducer array would be greatly assisted by any physical restraint on the lateral motion of the free edges of the individual transducer elements, while of course allowing full <u>independent</u> <u>axial</u> operation of neighboring transducer elements.

### Model Validation.

Although there was a fairly extensive empirical validation effort for the present modeling work, it cannot be presented herein due to space constraints. However, validation examples of the current modeling effort (in the form of an array Transmit Voltage Response (TVR) simulation) will be included in the oral presentation of this work.

## CONCLUSIONS

A new coupled structural-acoustic-piezoelectric FEA modeling approach is presented in this paper which investigates the structural dynamic response of a layered 1-3 piezocomposite half-wavelength underwater transducer array element. In particular, the cause for observed structural delamination failure of a recent experimental array element is investigated using this coupled modeling approach. The results show that (a) the edge conditions on the transducer array element have a potentially large impact on structural integrity and (b) that overall the present coupled modeling approach provides a useful methodology for designing and analyzing complex layered transducer array devices.

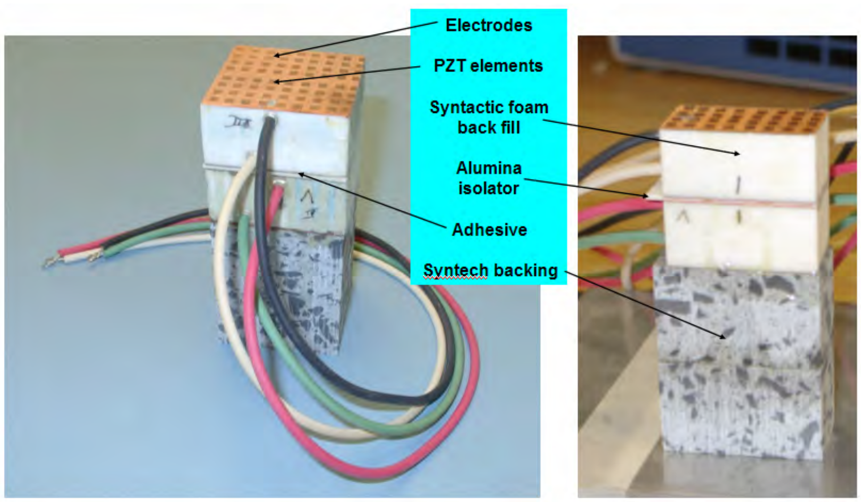



*Figure 1 - Photograph of 1-3 composite ½-λ resonator transducer element.*

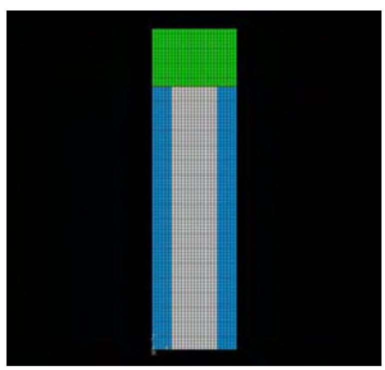


*Figure 2 - Single PZT cell FEA model*

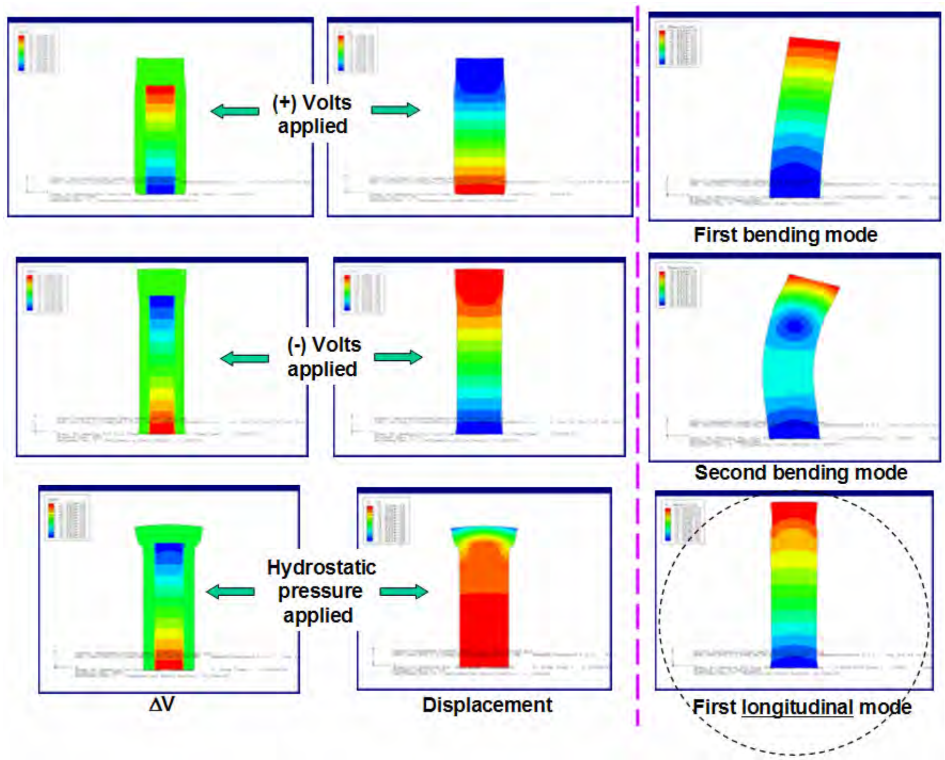
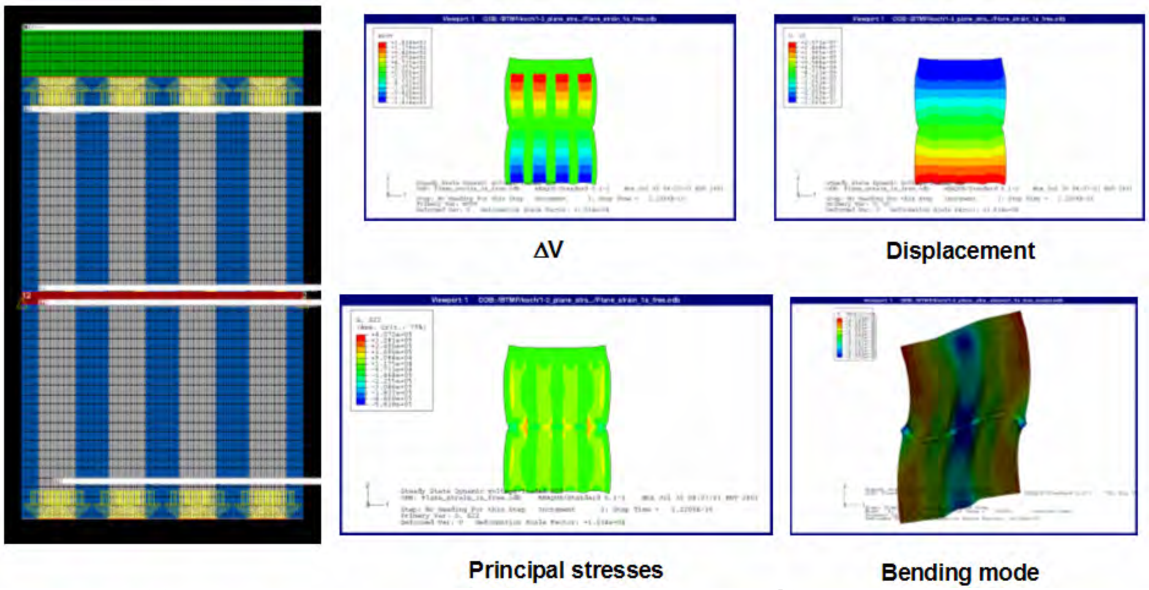



*Figure 3 - Single PZT cell FEA model canonical verification solutions (a) static, (b) modal*




*(a)* *(b)*

*Figure 4 - Two-layer/8 PZT cell FEA (a) model, (b) canonical verification solutions*

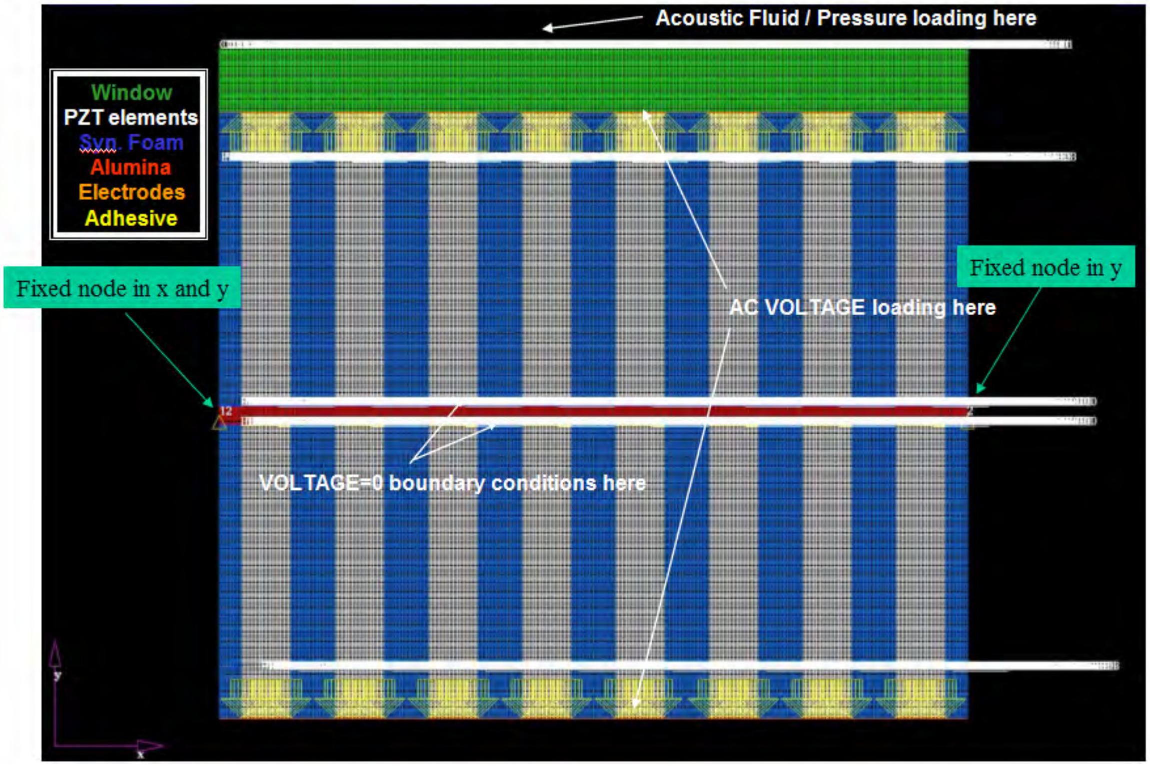
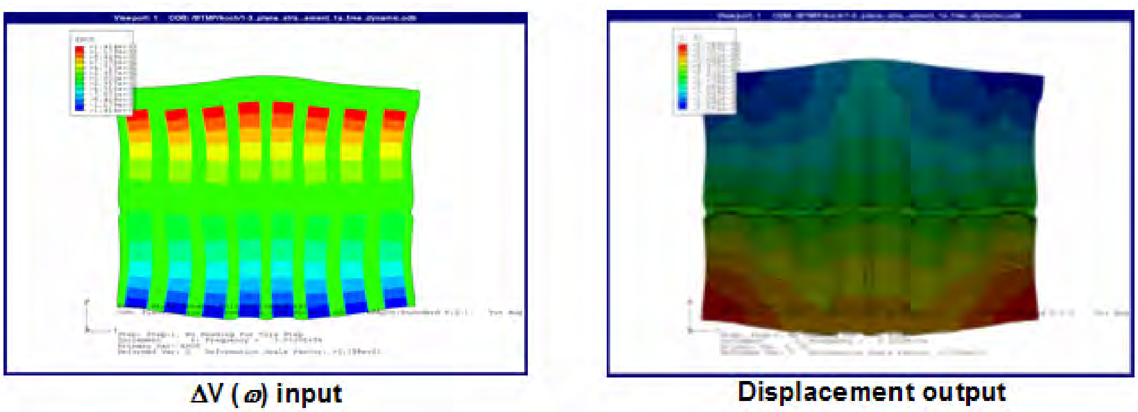



*Figure 5 - Two-layer/16 PZT cell transducer element FEA model showing "simply supported" and voltage boundary conditions*




*(a)* *(b)*

*Figure 6 - Two-layer/16 PZT cell transducer element FEA model showing (a) contour plot of SS dynamic input voltage, and (b) harmonic displacement response for* *<u>simply-supported case</u>*

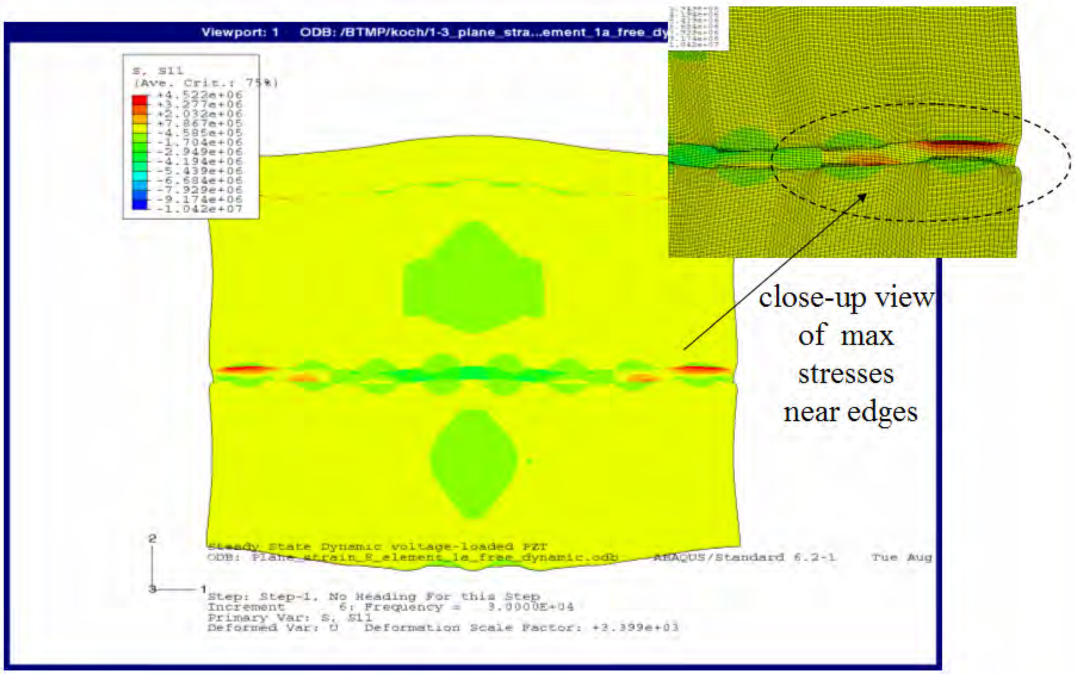



*Figure 7 - Two-layer/16 PZT cell transducer element FEA model showing resulting harmonic maximum Von Mises stress response for <u>simply-supported case</u>*

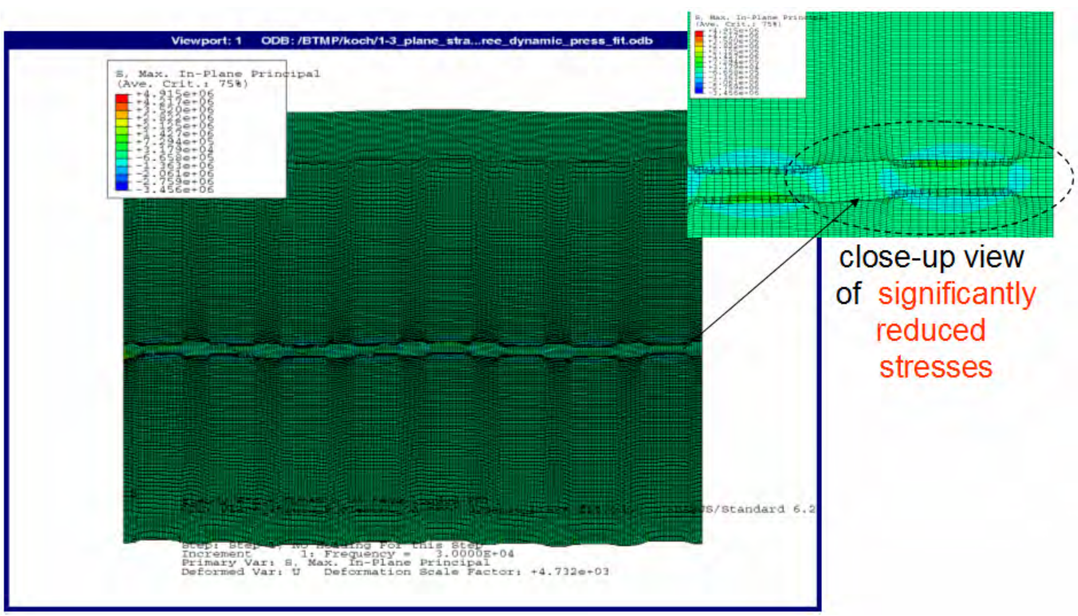



*Figure 8 - Two-layer/16 PZT cell transducer element FEA model showing resulting harmonic maximum Von Mises stress response for <u>"sliding press-fit" case</u>*