（様式３）

# 論文の内容の要旨

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## Analysis of 3D Intensity of Singular Stress Fields in Two-phase Transversely Isotropic Piezoelectric Bonded Joints
(２相横等方性ピエゾ接合体における３次元特異応力場の強さに対する解析)

In recent years, intelligent or smart structures and systems have drawn more and more attention. Piezoelectric materials are playing a key role as active components in many fields of engineering and technology. Mechanical stress occurs in piezoelectric material for any electric input. The stress concentrations caused by mechanical or electric loads may lead to crack initiation and extension, and sometimes the stress concentrations may be high enough to debond the material parts. Reliable service lifetime predictions of piezoelectric components demand a complete understanding of the debonding processes of these materials. When two materials are joined, a free-edge stress singularity usually develops at the intersection of the interface and the free surface. The stress singularity fields are one of the main factors responsible for debonding under mechanical or thermal loading. Stress singularity frequently occurs at a vertex in an interface of joints due to a discontinuity of materials. Stress singularity is related to debonding and delamination at interface of the bonded joints. Different numerical methods have developed for determining the singularity field in a 3D dissimilar material joint. Several studies have investigated the stress singularity field in 3D elastic materials. Recently, some researcher proposed the solution of singular stress field and its stress intensity factors of an interfacial corner of a 2D dissimilar piezoelectric material joint with crack. However, the singularity at a vertex in 3D transversely isotropic piezoelectric dissimilar material joints has not been made clear until now. In this study, the intensity of singularity at a vertex is investigated in transversely isotropic piezoelectric dissimilar material joints.

The orders of singularity at a vertex and at a point on singularity lines for piezoelectric bonded joints are determined using eigenanalysis based on FEM. Solving eigenequation yields many roots $p$ and eigenvectors corresponding to each eigenvalue are obtained. However, if the root $p$ is within the range of $0 < p < 1$, this fact indicates that the stress field has singularity. In the present analysis, the effect of material constants on the order of stress singularity is also examined. The angular functions of elastic displacement, electric potential, stress and electric displacement are calculated with the help of eigenanalysis. The numerical result shown that the angular functions of stress and electric displacement are larger at the free edge of the joints. The orders of stress singularity for two cases of isotropic piezoelectric material are also calculated. One case is an isotropic piezoelectric joint with piezo-effect and the other is that without piezo-effect. The largest value of $\lambda_{vertex}$ decreases in the isotropic joints.

The stress and electric displacement distributions on an interface in two-phase transversely isotropic piezoelectric dissimilar material joints are investigated using BEM. The distributions of stress and electric displacement with respect to radial distance, $r$ and angle, $\phi$ are plotted. The stress and electric displacement have a larger value at the vertex and near the free edge of the joint. Therefore, there is a possibility to debond and delamination at the corner and the interface edge of the bonded joints. The intensities of singularity are calculated by fitting the stress and electric displacement curves with the help of the result of eigenanalysis at the vertex. The intensities of singularity for stress and electric displacement are calculated by varying the material thickness in joints. It is shown from numerical result that the intensity of stress singularity increases with the thickness of upper material and the intensity of electric displacement singularity decreases with the thickness. The intensities of singularity for stress and electric displacement can be reduced significantly by varying the elastic and piezoelectric constants.

Finally, three-dimensional intensities of singularity for stress and electric displacement are determined. The 3D intensities of singularity are calculated using different boundary conditions and material combinations. It is shown from the present analysis that the 3D intensity of stress singularity increases and the 3D intensity of electric displacement singularity decreases with the increase of material thickness. Also the 3D intensities of singularity for stress and electric displacement are opposite to each other. It is observed from the present analysis that the value of $K_{1\theta\theta}^{3D}$ is larger than the value of $K_{1r\theta}^{3D}$ and $K_{1\phi\theta}^{3D}$. It is also found in the present analysis that the ratio of $K_{1r\theta}^{3D}$ and $K_{1\theta\theta}^{3D}$, and the ratio of $K_{1\phi\theta}^{3D}$ and $K_{1\theta\theta}^{3D}$ with respect to the material thickness in joints are nearly constant. This analysis reveals that the effect of the intensity of singularity at a 3D vertex for electric displacement on a thin material joint is larger than that of the thick material. Therefore, there is a highest possibility to debond and delamination at the corner of thin transversely isotropic piezoelectric bonded joints. It is also observed from the present analysis that the variations of material constants affect the intensities of singularity for stress and electric displacement more significantly.