INTERFACIAL DEBONDING BEHAVIOR OF

COMPOSITE BEAM/PLATES WITH PZT PATCH

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Abstract: This paper studies interfacial debonding behavior of composite beams bonded with piezoelectric material. The focus is put on crack initiation and growth of the piezoelectric adhesive interface. Closed-form solutions of interface stresses and energy release rates are obtained for adhesive layer in the piezoelectric composite beams. Finite element analyses have been carried out to study the initiation and growth of interfaces crack for piezoelectric beams with interface element by ANSYS, in which the interface element of FE model is based on the cohesive zone models to characterize the fracture behavior of the interfacial debonding. The results have been compared with analytical solution, and the influence of different geometry and material parameters on the interfacial behavior of piezoelectric composite beams have been discussed.

Key words: piezoelectric, interface crack, debonding, interface element, adhesive

1 Introduction

Piezoelectric materials have been increasingly used for applications in aerospace, navigation, civil and mechanical engineering[1]. Recently, piezoelectric ceramic (PZT) is
widely used to make sensors and actuators. When bonded or embedded into engineering structures, these PZT sensors and actuators are capable of controlling noise, vibration and shape\cite{2-4}, monitoring structural health, repairing structural defects \cite{5-6}, and acting as structurally integrated apertures\cite{7}. To understand the mechanical and electrical behaviour of structures incorporated with PZT sensors, some analytical analyses were carried out\cite{8-9}.

In practice, however, the bond may be weaken either in the process of manufacture because of the introduction of small flaws or during the service time when microcracks are induced under various conditions. Interface fracture or debonding is one of most common failure modes in this type of smart structures. Therefore the interface of piezoelectric smart structure has gained much attention.

In recent years, most research to date has focused on interfacial cracks between two different piezoelectric materials. The early attempt to analyze piezoelectric interface crack problem with fracture mechanics method is to model a finite crack at the interface of a piezoelectric material and a conductor subjected to a far-field uniform tension\cite{10}. To significantly simplify the calculations, the problem of an interface crack between dissimilar anisotropic piezoelectric materials has been analyzed by introducing a complex variable approach presented in later research\cite{11}. While cracks between piezoelectric actuators and elastic substrates have been rarely studied, especially for in-plane, mixed mode cases. Narita and Shindo\cite{12} and Kwon and Lee\cite{13} solved the anti-plane (mode III) problem of an interfacial crack between a piezoelectric material and an elastic material. A few analyses of the in-plane problem of interfacial cracks between a piezoelectric material and an elastic material exist. Kim and Jones\cite{14} conducted an analytical and experimental investigation to identify the
effects of debonding on the smart beam with PZT. Seeley and Chattopadhyay\cite{15} also performed the experimental investigation of composite beams with PZT actuation and debonding. Wang and Meguid\cite{16} utilized the solutions of a whole plane and a half plane subjected to a concentrated horizontal force for analyzing debonding effects of the embedded and bonded PZT patch. Tong and Luo\cite{17} based on the classic theory in bonding joints, a theoretical model for a PZT smart beam including adhesive layers is developed. M. Liu, K.J. Hsia\cite{18} study the interfacial crack between a piezoelectric actuator and an elastic substrate under in-plane electric loading. A closed form solution for stresses, electric field, and electric displacements along the bonded interface is obtained.

Although many essential investigations for such problems have been done with infinite dimensions by using analytical approaches, numerical studies of cracked finite size piezoelectric bodies are just under development. Various numerical techniques have been developed for fracture analysis of homogeneous piezoelectric materials, while the finite element method (FEM) is proved to be the most versatile numerical method, which can be used to study the influence of applied electric field and boundary conditions on the stress distribution at crack tips\cite{19-21}, since the intensity factors and energy release rates can be calculated conveniently. However, most of them don’t consider the effect of adhesive layer. In this paper, based on the Timoshenko beam-interface model and virtual crack closure integral (VCCI), we present an analytical approach to characterize the interface stress and energy release rates, and for the further study of interfacial debonding behavior of PZT composite beam, the numerical model and method are also established. Some typical
examples have been analyzed and discussed.

2 Adhesive interface model for PZT composite beam

2.1 Basic models and assumptions

We consider two semi-infinite length media, as a PZT layer bonded to the host beam on the top surface is shown in Fig. 1. In this model, the PZT layer and host beam are modeled as Timoshenko beams, and the adhesive layer is modeled as a continuous spring with the shear and peel stiffness. It is assumed that a straight crack propagate along midline of the adhesive layer that is sandwiched between PZT and host beam of different thickness. The poling direction of the piezoelectric material is along the negative z-axis. The free body diagrams for the infinitesimal elements of the PZT, adhesive layer and host beam are depicted in Fig. 2.

![Diagram 1](image1.png)

Fig.1. An interfacial crack in PZT composite beam.

![Diagram 2](image2.png)

Fig.2. Infinitesimal isolated body of the PZT beam system.
2.2 Fundamental formulation

By referring to Fig. 2, the equilibrium equations for PZT and host beam can be written as

\[
\frac{dN_1}{dx} = -\tau, \quad \frac{dN_2}{dx} = \tau \\
\frac{dQ_1}{dx} = -\sigma, \quad \frac{dQ_2}{dx} = \sigma
\]

\[
\frac{dM_1}{dx} = Q_1 - \frac{h_1}{2} \tau, \quad \frac{dM_2}{dx} = Q_2 - \frac{h_2}{2} \tau
\]

in which all the stress resultants are defined in Fig. 2. The subscripts 1, 2 in the above and all subsequent equations refer to the PZT, the host beam. \( h_1 \) and \( h_2 \) are the thickness of PZT and host beam; \( \sigma \) and \( \tau \) are the interface shear and peel stresses.

By employing the mechanical-electrical relations of PZT\textsuperscript{[23]} and the Timoshenko beam\textsuperscript{[24]} theory, we can obtain the following constitutive relations for the PZT and the host beam as

\[
N_1 = A_i \frac{du_i}{dx} + e_{31}V, \quad N_2 = A_i \frac{du_i}{dx} \\
Q_i = B_i (\phi_i - \frac{dw_i}{dx}) \\
M_i = -D_i \frac{d\phi_i}{dx}
\]

where \( e_{31} \) and \( V \) are a PZT coupling constant of the PZT and the applied voltage; where \( A_i, B_i \) and \( D_i \) (\( i = 1, 2 \)) are the extensional, shear and bending stiffness of PZT and host beam, respectively, expressed as

\[
A_i = E_i h_i, \quad B_i = \frac{5}{6} G_i h_i, \quad D_i = \frac{1}{12} E_i h_i^3
\]
where $E_i$ and $G_i$ ($i = 1, 2$) are Young’s modulus and shear modulus of PZT and host beam.

In the adhesive layer, the definition given by Goland and Reissner\textsuperscript{[25]} and Tong and Steven\textsuperscript{[26]}, we have the constitutive relations for the adhesive layer, the peel stress $\sigma$ and the shear stress $\tau$ are assumed to be

$$
\sigma = K_p (\Delta w) = K_p (w_2 - w_1)
$$

$$
\tau = K_s (\Delta u) = K_s \left[ (u_2 - u_1) + \left( \frac{h_1}{2} \phi_1 + \frac{h_2}{2} \phi_2 \right) \right]
$$

(4)

Where $\Delta u$ and $\Delta w$ are interface displacement jumps between PZT and host beam; $K_s, K_p$ are the shear and peel stiffness; $t_a$ is the adhesive thickness; $E_a$ and $G_a$ are the Young's and shear moduli of the adhesive layer.

Combining Eqs. (1), (2) and (4) and then substitute into Eq. (4), the governing equation of the problem that expressed in terms of shear and peel stresses is established as:

$$
\frac{d^3 \tau}{dx^3} = a_1 \frac{d \tau}{dx} + a_2 \sigma
$$

$$
\frac{d^4 \sigma}{dx^4} = a_3 \frac{d^2 \sigma}{dx^2} - a_4 \sigma - a_5 \frac{d \tau}{dx}
$$

(5)

where

$$
\begin{align*}
 a_1 &= K_s \left( \frac{1}{A_1} + \frac{1}{A_2} + \frac{h_1^2}{4D_1} + \frac{h_2^2}{4D_2} \right), \\
 a_2 &= K_s \left( \frac{h_1}{2D_1} - \frac{h_2}{2D_2} \right), \\
 a_3 &= K_p \left( \frac{h_1}{2D_1} - \frac{h_2}{2D_2} \right), \\
 a_4 &= K_p \left( \frac{1}{D_1} + \frac{1}{D_2} \right), \\
 a_5 &= K_p \left( \frac{1}{B_1} + \frac{1}{B_2} \right)
\end{align*}
$$

(6)
2.3 Solution of the coupled equation (5)

Combining both equations in Eq. (5), by eliminating the peel stress, we have an ODE of six-order for the shear stress, then the governing differential equation can be solved using the characteristic equation:

\[ R^6 + k_1R^4 + k_2R^2 + k_3 = 0 \]  \hspace{1cm} (7)

in which

\[ k_1 = -\left(a_1 + a_2\right), \quad k_2 = a_4 + a_4a_5, \quad k_3 = -\left(a_4a_5 - a_2a_5\right) \]  \hspace{1cm} (8)

there always exist one real number root and two conjugate complex number roots for the most combinations of typical material properties and geometric configurations. Therefore, we can express solutions to the shear and peel stresses as:

\[ \tau = C_1e^{-R_1x} + C_2\cos \left( R_3x \right) + C_3\sin \left( R_3x \right) + C_4 \]
\[ \sigma = C_1T_te^{-R_1x} + C_2\left[T_2\cos \left( R_3x \right) - T_3\sin \left( R_3x \right)\right] + C_3\left[T_2\sin \left( R_3x \right) + T_3\cos \left( R_3x \right)\right] \] \hspace{1cm} (9)

where \( C_i \) \( (i = 1, 2, 3, 4) \) are the unknown coefficients to be determined by the boundary and continuity conditions. \( T_i \) \( (i = 1, 2, 3) \) can be found by substituting Eq. (9) into (5), as follows:

\[ T_1 = \frac{a_1R_1 - R_1^3}{a_2}; \quad T_2 = \frac{-\left(a_1R_2 - R_2^3 + 3R_2R_3^2\right)}{a_2}; \quad T_3 = \frac{-\left(a_4R_3 + R_3^3 - 3R_3R_4^2\right)}{a_2} \] \hspace{1cm} (10)

The boundary conditions for problem shown in Fig. 1 can be defined as:

\[ x \to \infty; \quad \tau = 0; \quad \sigma = 0 \]
\[ x = 0; \quad \frac{d\tau}{dx} = H_n; \quad \frac{d^2\sigma}{dx^2} - a_5\sigma = H_m; \quad \frac{d^3\sigma}{dx^3} - a_5 \frac{d\sigma}{dx} + a_5\tau = H_q \] \hspace{1cm} (11)
where

\[
H_n = K_s \left[ \left( \frac{N_2}{A_2} - \frac{N_1}{A_1} - \frac{e_2 V}{A_1} \right) - \left( \frac{h_3 M_2}{2D_2} + \frac{h_3 M_1}{2D_1} \right) \right]
\]

\[
H_m = -K_p \left( \frac{M_2}{D_2} - \frac{M_1}{D_1} \right), \quad H_q = -K_p \left( \frac{Q_2}{D_2} - \frac{Q_1}{D_1} \right) \quad (12)
\]

In Eq. (11), a semi-infinite length of the adhesive bonded PZT layer on the top surface of the host beam is assumed. When the adhesive layer is very thin, Eq. (11) may also be applicable to the relatively long PZT-adhesive-beam case. It is worth noting the peel stress and shear stress in the adhesive layer far from the crack tip at the other edge is not zero when PZT layer under electric loading\(^ {17,18} \), however, we can assume it to be zero where far from crack tip, because it is not causing stress redistributions in the vicinity of the crack tip in light of the Saint Venant principle. The boundary conditions shown in Eq. (11) are the prescribed force boundary conditions at the cross section of the crack tip as shown in Fig. 1, which can be determined from either equilibrium conditions.

Substituting Eq. (9) into (11), we find \( C_4 = 0 \), and then the following linear algebraic equations can be derived:

\[
T_{11} C_1 + T_{12} C_2 + T_{13} C_3 = H_n
\]

\[
T_{21} C_1 + T_{22} C_2 + T_{23} C_3 = H_m \quad (13)
\]

\[
T_{31} C_1 + T_{32} C_2 + T_{33} C_3 = H_q
\]

where

\[
T_{11} = -R_1; \quad T_{12} = -R_2; \quad T_{13} = R_3
\]
\[ T_{21} = T_1 \Big( R_1^2 - a_5 \Big) ; T_{22} = R_2^2 T_2 - 2 R_2 R_3 T_3 - R_3^2 T_2 - a_5 T_2 ; T_{23} = R_2^2 T_3 - 2 R_2 R_3 T_2 - R_3^2 T_3 - a_5 T_3 \]

\[ T_{31} = -T_1 R_1^3 + a_5 T_1 R_1 + K_3 ; T_{32} = -R_2^2 T_2 + 3 R_2^2 R_3 T_3 + 3 R_2 R_3^2 T_2 + R_3^2 T_3 - a_5 \left( R_3 T_3 - R_2 T_2 \right) + K_3 \]  

(14)

\[ T_{33} = -R_3^2 T_3 + 3 R_3^2 R_4 T_4 + 3 R_2 R_3^2 T_4 + R_3^2 T_3 - a_5 \left( R_3 T_3 - R_2 T_2 \right) \]

Then, the coefficients \( C_i \) \((i = 1, 2, 3)\) are obtained as:

\[
\begin{pmatrix}
C_1 \\
C_2 \\
C_3
\end{pmatrix} = \frac{1}{Y} \begin{pmatrix}
T_{22} T_{33} - T_{32} T_{23} & T_{13} T_{32} - T_{12} T_{33} & T_{23} T_{12} - T_{13} T_{22} \\
T_{23} T_{31} - T_{21} T_{33} & T_{13} T_{31} - T_{11} T_{33} & T_{21} T_{33} - T_{13} T_{13} \\
T_{21} T_{32} - T_{22} T_{31} & T_{12} T_{32} - T_{13} T_{32} & T_{22} T_{12} - T_{12} T_{22}
\end{pmatrix} \begin{pmatrix}
H_u \\
H_w \\
H_y
\end{pmatrix}
\]  

(15)

where \( Y \) is the determinant of the coefficient matrix of Eq.(14)

### 2.4 Energy release rate for the interface crack

According to the virtual crack closure integral (VCCI) method developed by Irwin (1957), for a crack, the strain energy released by extending a crack by an infinitesimally small amount \( \Delta a \) is equal to the energy required to close the crack by the same amount. Therefore, the energy release ratio can be approximated as given by Eq. (16)

\[
G_I = \frac{1}{2} K_p \left[ \Delta w(0) \right]^2 = \frac{t_u}{2 E_u} \left[ \sigma(0) \right]^2
\]

\[
G_{II} = \frac{1}{2} K_s \left[ \Delta u(0) \right]^2 = \frac{t_u}{2 G_u} \left[ \tau(0) \right]^2
\]  

(16)

### 3 Finite element analysis of PZT composite beam

#### 3.1 Finite model

The numerical simulations of the interfacial debonding in a real geometric configuration
of the PZT composite beam were carried out with the aid of the finite element method (FEM) in the commercial code ANSYS. 2-D piezoelectric coupled-field solid element(PLANE13) and 4-node structural plane element(PLANE182)were used to mesh the PZT adhesive beam. The analysis was performed under plane stress condition. Accordingly, the elements along the interface are defined as cohesive elements. The corresponding constitutive relation of a CZM, the traction–separation relation of cohesive law, is implemented through the 2-D 4-Node interface element (INTER202). As interface element can not be used in conjunction with piezoelectric solid element, we use a very thin layer with PLANE182 element between them, and have the same material properties as PZT. In the numerical model, the quadrangular element size is equal to half length of the adhesive thickness, approximately. Convergence analysis has shown that the element mesh provides good approximation of results. The following material parameters used for these calculations: PZT: \( E_i = 70 \text{ GPa}, \ G_i = 30 \text{ GPa}, \ e_{31} = -5.2 \text{ N/mV}, \) Adhesive layer: \( E_a = 3 \text{ GPa}, \ G_a = 1 \text{ GPa}; \) Host beam: \( E_2 = 70 \text{ GPa}, \ G_2 = 30 \text{ GPa}. \) In the calculations, PZT length equal to 40mm, beam length equal to 60 mm. In considering influences of the thickness ratios, we let that \( h_i \) be equal to 1 mm.

![Fig.3. PZT composite beam model with interface crack.](image-url)
### 3.2 The cohesive zone model

Interfacial debonding growth can be simulated by placing interfacial elements between the PZT layer and the adhesive layer. The exponential cohesive zone model (CZM) implemented in the interface element of ANSYS is one that is commonly adopted. The interface is characterized by constitutive equations which relate the applied stress $T$ to the relative displacement at the interface $\delta$. For the exponential CZM, an interfacial potential is defined by

$$\phi(\delta) = e\sigma_{\text{max}} \delta_n \left[ 1 - (1 + \Delta_n) e^{-\Delta_n} e^{-\Delta_i} \right]$$

where: $\phi(\delta)$ is the surface potential, $\sigma_{\text{max}}$ is the maximum normal traction at the interface $\Delta_n = \delta_n / \delta_n$, $\Delta_i = \delta_i / \delta_i$; $\delta_n$ is the normal separation across the interface, $\delta_i$ is the shear separation across the interface. The relations between the traction across an interface and the potential are:

$$T_n = \frac{\partial \phi(\delta)}{\partial \delta_n}, \quad T_i = \frac{\partial \phi(\delta)}{\partial \delta_i}$$

Substituting Eq. (17) into Eq. (18) gives the interfacial tractions as follows:

$$T_n = e\sigma_{\text{max}} \Delta_n e^{-\Delta_n} e^{-\Delta_i}, \quad T_i = e\tau_{\text{max}} \Delta_i \left( 1 + \Delta_n \right) e^{-\Delta_n} e^{-\Delta_i}$$

The normal and tangential works of interface separation are given by

$$\phi_n = \sqrt{2e\sigma_{\text{max}}} \delta_n, \quad \phi_i = \sqrt{2e\tau_{\text{max}}} \delta_i$$

### 4 Results and discussions
4.1 Interface shear and peel stresses

To investigate performance under electric loading (PZT as a actuator), we assume that there are no applied mechanical forces on the structures and that only a voltage of negative 100V is applied to PZT shown in Fig. 1. The interfacial peel and shear stresses, which transfer the actuation energy between the actuator and the host beam, can be determined directly from the solution given in the previous section.

Fig. 4. Peel stress distribution along the PZT beam in the interface with $h_l/t_a=10$ and $h_2/h_1$ ranging from 1 to 30.

Fig. 5. Shear stress distribution along the PZT beam in the interface with $h_l/t_a=10$ and $h_2/h_1$ ranging from 1 to 30.

Figs. 4 and 5 depict the stress distributions from the crack tip ($x=0$) for the PZT composite beams along the interface with a fixed PZT layer-to-adhesive thickness $h_l/t_a=10$, and with host beam-to-PZT layer ratio $h_2/h_1$ varies from 1 to 30. It is clearly shown that, for the given material properties and thickness of the adhesive layer, for larger thickness ratio $h_2/h_1$ tends to create larger peak shear and peel stresses at the crack tip, and it is shown slightly affect the interlayer peel and shear stress. For this reason, the beam with small
thickness of PZT layer and large thickness of elastic material will be debonding easily. And we also can find the peak value of the peel stress is in the same order as that of shear stress, indicate the importance of the peel stress, and it will lead to the mix mode fracture of PZT composite beam.

Figs. 6 and 7 show the influence the PZT layer-to-adhesive thickness ratio $h_l/t_a$ varies from 1 to 30, while with a fixed host beam-to-PZT layer thickness ratio $h_a/h_l = 10$. The distribution curves for both shear and peel stresses are the same as those presented in Figs. 4 and 5. It is clearly shown that, for the given material properties and thickness of the host beam and the PZT, a thinner adhesive layer tends to create larger peak shear and peel stresses while a thicker adhesive layer seems to yield smaller peak shear and peel stresses at the crack tip.

4.2 Energy release rates

The key parameters of the CZM include cohesive strength, work of separation, and the interface characteristic length parameter. Preliminary calculations reveal that the numerical
results are less sensitive to the interface characteristic length parameter, $\delta_n$, compared to the cohesive strength. For this reason, $\delta_n$ is set to 0.002 $\mu$m in all of the simulations using the exponential CZM, and this choice of $\delta_n$ is able to ensure the convergence of the simulations as well. In contrast to $\delta_n$, the cohesive strength has a prominent influence on the simulation results. Based on analytical solution above, reasonable value for the crack tip is calculated of different geometric configuration, so we can use the peak value of interface stress of PZT composite beam as $\delta_{\text{max}}$ and $\tau_{\text{max}}$. In order to better describe the simulation results of PZT interface delamination behavior, relative small values of $\delta_{\text{max}}$ and $\tau_{\text{max}}$ ($h_2/h_i = 2$) are selected and calculate with different geometric configuration.

Fig.8. Energy release rates for crack length with different thickness $h_2/h_i$.

Fig.9. Energy release rates for crack length with different adhesive elastic modulus.

Fig.8. shows the energy release rates for crack growth with different host beam-to-PZT layer thickness ratio $h_2/h_i$. It can be seen that the energy release rates decrease as the values of ratios of thickness and crack length increase. When crack length small the energy release rates decrease small, but with debonding continues developing, the energy release
rates decrease dramatically, especially for large thickness ratio \((h_z/h_l \geq 10)\). In addition, we find the energy release rate can be very close for small thickness ratio with analytical solution as relatively long PZT adhesive beam case. Fig. 9 shows the energy release rate of the crack growth with different adhesive elastic modulus. The energy release rate decreases as the crack growth, the value of energy release rates are close when the crack increases small length for different adhesive elastic modulus, but with it continues growth, the effect of adhesive elastic modulus is very much. If PZT actuator is used to the structural shape control, the shape will almost maintain the same in this case. However, when the debonding continues developing, the energy release rates will decrease. When the energy release rates decrease to the values below the critical bonding energy, the debonding will stop by self. This mechanism is the self-arresting behavior, which is the same as that concluded by Wang and Meguid\(^{[16]}\).

Fig. 10. Mode ratio \((G_{II}/G_I)\) versus different thickness with different thickness \(h_z/h_l\)

Fig. 11. Mode ratio \((G_{II}/G_I)\) versus different crack length under shear forces effect.

Fig. 10 shows the mode ratio \(G_{II}/G_I\), versus thickness ratio \(h_z/h_l\) for different thickness ratio \(h_l/t_a\) together with that obtained based on the analytical solution taken from Eq.(16).
When PZT as actuator, it depend on the interaction between these two modes, and the mode ratio $G_{II}/G_I$ decreases with the thickness of beam increase and adhesive layer thickness decrease, but decreasing rate gradually slows down and eventually tending to a constant value. It clearly indicates the effects of thickness ratio on the mode ratio of the energy release rates for the interface crack, we can find that the thickness ratio significantly affects the energy release rates, particularly for the beam with small thickness ratio ($h_2/h_1 \leq 10$) and thin adhesive layer thickness ($h_1/t_a \geq 10$). Adhesive fracture analysis of PZT actuator composite structure must take into account the almost certain likelihood of the presence of both modes I and II fracture.

To investigate the shear force effects and influence of the crack growth to the interface of the PZT actuator beam, we consider the problem of at the free edge of beam subjected to a shear forces $P = 100 \text{ N}$, so $Q_x = P$, $M_2 = Pa$ as shown in the in Fig. 1. Fig. 1 clearly indicates the effects of shear force and ratios of thickness $h_2/h_1$ on the mode ratio of the energy release rates for the interface crack when PZT as an actuator. When the shear force are applied to beam, mode ratio $G_{II}/G_I$ decreases with the crack length, but decreasing rate is very slowly. The thickness ratio is considerably influences the interface fracture. The comparison shows a difference between the finite element and analytical results, the trend is similar. The analytical formulation that here has been presented is therefore approximated, so that it can be used for a first evaluation of the energy released at the crack tip and with a small length growth.
Conclusions

This paper presents simple, closed-form and novel formulas for calculating interface stresses and mode I and II energy release rates for an interfacial straight crack in PZT composite beams. The stresses and energy release rates in are expressed in terms of a generic material and geometry combination as well as an arbitrary combination of axial loads, bending moments and transverse shear forces acting on the PZT composite beam at the cross section of the interface crack tip. In FEM analysis, interface element is use to model the debonding of adhesive interface with exponential cohesive zone model. The conclusions, based on the results and observations on the variations of the interface stress and energy release rate, are as follows:

1. When PZT as a actuator, the peel stress is as important as shear stress at crack tip, especially for a thick beam or a thin adhesive layer. For this reason, beam with small thickness of PZT layer and large thickness of elastic material or thin adhesive layer will be debonding easily.

2. The energy release rate is decreased with crack growth, when it below the adhesive, the growth stop by itself under electric loading. And the thickness ratio and adhesive material properties are considerably influences the interface fracture. The mix mode ratio \( G_{II}/G_I \) also demonstrates that the fracture toughness of PZT composite structure must take into account the presence of both modes I and II fracture.

3. Our study demonstrated the applicability of the interface element with cohesive zone
model in characterizing the interface debonding behavior of PZT composite structure.

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