Effect of Adhesive Debonding on Static and Dynamic response of PZT Bonded Aluminium Beam

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Abstract. Piezoelectric actuators and sensors have been extensively used in smart structures. A structure becomes smart when piezoelectric patches are either surface bonded or embedded into the host structure. Under the application of electric potential piezoelectric materials may expand/contract, which serves them as an actuator. Similarly, when it gets strained, an electric potential is induced, which serves them as sensors. Piezoelectric materials (PZT) are usually surface bonded to the structures using suitable bonding agents. This bonding agent plays a crucial role in transferring the forces from the piezoelectric layer to the host layer. This paper presents the effect of adhesive debonding on static as well as dynamic response of PZT bonded aluminium beam. The results show that debonding failure adversely affects the actuating capabilities of the PZT transducer. It is seen that the tip displacement decreases with increase in debonding size. The results also highlight that neglecting the adhesive layer in the finite element (FE) models overestimates the tip displacement as well as its natural frequencies.

1. Introduction
The ability of piezoelectric transducers to convert electrical loads to mechanical effects and vice versa has made them applicable for various engineering applications such as vibration control, energy harvesting, shape control, structural health monitoring (SHM) etc. Piezoelectric patches (PZT) are superior compared to other transducers due to distinct features like high force-to-weight ratio, fast response, low power consumption and high sensitivity. Moreover, they can be quickly bonded/embedded into structures, and they possess broad operating bandwidths [1,2]. Piezoelectric sheets are generally attached to the host structure using appropriate bonding agents, which provides a medium for strain transfer between the PZT layer and the host structure. The effect of the adhesive layer on the interaction between the PZT layer and the host structure has been studied recently by various researchers using experimental and numerical investigations [3-6]. During the service life of any PZT bonded structures, piezoelectric transducers get detached from the host structure due to prolonged use, temperature change, high peeling stress concentration at the adhesive edge, poor bonding agents etc. As a result of debonding, the sensing and actuation abilities of PZT transducers may get affected. Hence it is essential to investigate the consequence of adhesive debonding on the static and dynamic response of PZT bonded structures. Recently, the effect of debonding on stress transfer between PZT and host structure is studied by Yu and Wang [7]. Raja et al. [8] studied the effect of edge debonded actuator on the transverse deflection of the piezoelectric beam under different boundary conditions. Liu et al. [9] experimentally investigated the effect of the actuator as well as sensor debonding in SHM systems. A comprehensive analysis tool is developed by Hosking and Sotoudeh [10] to study the dynamic and aeroelastic behaviour of PZT attached beam. However, here the effect of the adhesive layer is not considered. In most of the past studies, the effect of the bonding layer is neglected, or its debonding effects are studied either by 1D or 2D analytical or numerical models. Since most of the piezoelectric materials are orthotropic, a three-dimensional analysis is necessary to evaluate the performance of...
debonded smart beams. This paper presents a three-dimensional numerical simulation of a smart aluminium beam with partially debonded PZT actuator. Static analysis is carried out to examine the effect of partial debonding of the piezoelectric patch on tip deflection. Nine different debond configurations are considered for the study. Additionally, the effect of the engineering properties of the bonding layer and the effect of its thickness were also evaluated. Eigenvalue analysis is also performed to extract the natural frequencies for a fully bonded as well as partially debonded smart cantilever beam.

2. Finite element model
The PZT bonded aluminium beam illustrated in figure 1 is used for the current study. The beam is 152.4 mm long, 25.4 mm wide and is fixed at its left end. The aluminium beam is 15.24mm thick, while the bonding layer and PZT layer thicknesses are 0.254 mm and 1.524 mm, respectively. For details regarding the material properties of smart beams, refer to [11]. The top surface of the PZT layer is imposed with a voltage of 12.5 kV while the bottom surface is grounded.

![Figure 1. The geometry of the smart cantilever beam.](image1)

The behaviour of the PZT bonded smart beam is studied using commercially available FE software Abaqus CAE. The 3D numerical model of the smart beam is shown in figure 2. A linear hexahedral element is utilised to discretise the aluminium and bonding layer, while a linear piezoelectric hexahedral element is used to discretise the piezoelectric layer. A mesh refinement study was conducted initially to arrive at an optimum number of finite elements. A total of 3660 elements is chosen for the PZT layer and adhesive layer, while 8700 elements were used for the aluminium layer. To avoid any relative motion between the layers, tie constraints are assigned at the interface.

![Figure 2. 3D finite element model of the PZT bonded smart beam.](image2)

![Figure 3. Comparison of the transverse displacement along the length of the beam.](image3)

For validating the numerical model, the transverse displacement along the length of the beam obtained by finite element analysis is compared with the solutions attained by Wang and Yu [11]. The comparison of transverse deflection is shown in figure 3. It is noticed that excellent agreement exists between the results. Hence the current FE model is used for additional studies. Various debond configurations are considered to study the effect of debonding. Case 1 – debond along the length of PZT, case 2 – debond along the width of PZT and case 3 – Debond along both length and width of PZT. For each case, the percentage of debond area is taken as 0%, 25% and 75%. The different partial debond configurations with 50% debond area is displayed in figure 4.
3. Results and Discussion

3.1. Influence of partial debond on tip deflection

Figure 5 shows the variation in tip displacement for different debond cases. It is noted that for all the cases, the tip displacement decreases with increase in percentage debond area. However, the percentage reduction in tip displacement for central debond is less compared to the edge, and double edge debond. The maximum percentage reduction for central debond is obtained as 12% for debond case 2 with 75% debond area. This indicates that the central debond, which is challenging to visualise and identify, does not cause many effects in the static response. The worst situation under all the cases considered is for debond case 1 with double edge debond. Here the percentage reduction in tip displacement is obtained as 81% for 75% debond area. This decrease is due to the reduction in the stiffness of the adhesive layer. When the adhesive gets degraded, the efficiency of the bonding layer in transmitting the forces to the host layer from the piezoelectric layer reduces.

Figure 5 shows the variation in normalised tip displacement for (a) Debond case 1 (b) Debond case 2 and (c) Debond case 3.
3.2. Influence of partial debond on natural frequencies

The system’s natural frequencies and their corresponding mode shapes are also studied for the healthy as well as for different debonding cases. It is found that the presence of debonding decreases the natural frequencies, and by increasing the debonding size, the natural frequencies decrease for all higher modes. Figures 6 and 7 show the variation in first and twentieth natural frequencies, respectively, for different debond cases. It is observed that for debond case 2, the percentage reduction in first natural frequency is less compared to the other two cases. The maximum percentage reduction when debond is considered along the width of PZT (debond case 2) is 5% for 75% debond area. It is also noted that the edge debond is most critical under all debond cases. A maximum percentage reduction of 85% is obtained for debond case 1 with edge debond (75% debond area). The results also highlight that the debond cases with central debond do not have much effect on the first natural frequency. A maximum percentage reduction of 11% is obtained for debond case 1. To study the effect of debonding at high frequencies, the variation in 20th natural frequency is plotted with different debonding size. Figure 6 shows the change in 20th natural frequency for different debond cases. It is seen that for almost all debond cases, there is a considerable reduction in natural frequency. A maximum percentage reduction of 78% is obtained for debond case 3 with 75% debond area.

![Figure 6. Variation in 1st natural frequency for (a) Debond case 1 (b) Debond case 2 and (c) Debond case 3.](image)

![Figure 7. Variation in 20th natural frequency for (a) Debond case 1 (b) Debond case 2 and (c) Debond case 3.](image)

3.3. Influence of engineering properties of bonding agent

Piezoelectric materials are attached to the host structure using various kinds of bonding agents viz. thermoplastic tape, silver epoxy, Loctite adhesive, instant glue and Araldite epoxy [12]. The selection of a specific bonding agent is vital for achieving an ideal coupling between the host layer and the piezoelectric layer. The coupling governs the capability of the piezoelectric patches in actuating and receiving voltage signals. The structural adhesives available in the market can broadly be classified into...
three types A1, A2 and A3 [13]. Adhesives – A1 is classified under the rubbery region. These have a higher Poisson’s ratio of \( \nu = 0.49999 \) and a lower Young’s modulus of \( E = 0.001 \) GPa. Adhesives- A2 are classified under rubber-to-glass transition region which has an intermediate value of \( \nu = 0.4 \) and \( E = 1.0 \) GPa whereas adhesives – A3 in the glassy region have a lower Poisson’s ratio of \( \nu = 0.3 \) and higher Young’s modulus of \( E = 10 \) GPa. Figure 8(a) shows the variation in tip displacement for different adhesive types. It is observed that maximum tip displacement is obtained for adhesive type A3 whereas for adhesives A1 and A2 the percentage reduction in tip displacement is obtained as 97% and 9% respectively. The change in first and fiftieth natural frequency for different types of adhesives is plotted in figure 8(b) and (c) respectively. The natural frequency obtained for adhesive A1, A2 and A3 is 465.8 Hz, 532.18 Hz and 545.3 Hz, respectively.

![Figure 8](image)

**Figure 8.** Effect of adhesive types on (a) tip deflection (b) first and (c) fiftieth natural frequency.

### 3.4. Effect of thickness of the adhesive

Shear lag is one of the unavoidable phenomena that occurs due to the presence of the bonding layer in smart structures. The previous studies indicate that as the bonding layer thickness increases, the effect of shear lag becomes more dominant [14]. The transfer of shear force between the host layer and the piezoelectric layer in such cases becomes less efficient. Figure 9(a) shows the variation in tip displacement for different bonding layer thickness. It is seen that the magnitude of tip displacement decreases with an increase in adhesive thickness. From figure 9(b) and (c) it is observed that the natural frequency also gets affected due to increased adhesive thickness. It is also realised that without considering the adhesive layer, the system overestimates its natural frequencies.

![Figure 9](image)

**Figure 9.** Effect of thickness of bonding agent on (a) tip displacement (b) first and (c) fiftieth natural frequency.

### 4. Conclusions

This paper presents the effect of adhesive debonding on the static and dynamic response of PZT bonded aluminium beam. A three-dimensional numerical study is done to investigate the effect of partial debonding on tip deflection and the natural frequencies of the smart cantilever beam. It is noted that the efficacy of the bonding layer on stress transfer between the host layer and piezoelectric layer depends on adhesive layer stiffness. Hence, partial debonding significantly alter the actuating capabilities of PZT actuator as well as its natural frequencies. The partial debonding effects are also substantial at high
frequencies. The numerical results also emphasise the significance of considering the bonding layer in the finite element model. Also, it is observed that the system overestimates its natural frequencies if the bonding layer is neglected.

5. References
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