

# 3D vs 2D Modeling of the Effect of Die Size on Delamination in Encapsulated IC Packages

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## Abstract

In a previous 2D parametric study, it was found that the die size appear to have no significant effect on the likelihood of delamination at the pad-encapsulant interface in a plastic-encapsulated IC package. This trend appears to be counter intuitive since in practice, it is known that larger dies are more likely to delaminate in comparison with smaller ones. The authors had speculated that this could be due to the limitations of 2D analysis. Hence this finding is re-investigated using 3D analysis. In this parametric study, 3D finite element models that incorporate an initial delamination a corner delamination of different shapes (concave, convex, straight) were analyzed. The geometric parameters varied include the size of the pad, the die and the package. Both the energy release rate and mode mixity were calculated. It was found that in 3D analysis, different shapes of initial delaminations result in similar trends in the propensity to delaminate from the corners. From the results of the 3D analyses of a package with an initial corner delamination, it was found that increasing the die size leads to an increase in ERR, and hence an increase in the likelihood of delamination from the corners of a package. This trend is in contrast to that predicted from the 2D analyses, that ERR do not increase with increasing die sizes. The above findings seem to suggest that for predicting delamination from the corners of a package, which is usually where the highest stress is located, only a 3D analysis will be adequate.

## Introduction

Delamination is a common problem in plastic-encapsulated IC packages. Numerical simulations are especially useful in the design phase where a particular design of the package or a suitable kind of material needs to be selected since an experimental evaluation can be more expensive. Parametric analyses that involved the variation of geometric parameters are often carried out to determine the package design that is the most resilient to failure. Findings from past research [1-4] highlighted that geometric parameters can have significant impact on the crack driving force. Using 2D models, Tay and Zhu [1,2] performed comprehensive parametric studies on the effect of various geometric parameters on the propensity to delaminate. Xie et. al. [3] studied the impact of substrate thickness on the vapor pressure during solder reflow and found that the vapor pressure of a thick and thin substrate remains about the same except at temperatures greater than 250°C. Yong et. al. [4] obtained maximum stress for different die attach thicknesses from 3D simulations and made use of

2D models for fracture mechanics study. It was found that increasing die attach thicknesses will significantly reduce die attach stresses. Past simulations typically assumed a 2D plane strain model especially for linear elastic fracture mechanics study since 3D parametric analyses can be very time-consuming. Even when 3D finite element models are used in parametric analysis, the conclusions drawn is seldom compared to the ones obtained from 2D analyses. No detailed studies had been done to date. It is unclear as to whether geometric parameters will influence the shape of the crack front or whether parametric studies performed by 2D models and 3D models will lead to the same conclusion.

Comparing 2D and 3D interfacial fracture mechanics study of an IC package under thermal loading, their differences can be separated to 3 different categories. One is that for a 3D model, the global deformation is different from 2D model. 2D models are able to bend only about one axis while 3D models are able to bend about two different axes resulting in a more complex deformation pattern. Secondly, fracture mechanics parameters from 2D models are influenced by the edge while in 3D models they are influenced by both edges and corner. Thirdly, in a 2D fracture mechanics study, the assumed delamination is a line, which physically in 3D is equivalent to a rectangular strip, while in a 3D analysis the delamination can be of any arbitrary shape that one can specify. The interplay of the above differences may lead to different conclusions drawn from 2D and 3D parametric studies. To investigate the above, several parameters are investigated and the energy release rate and mode mixity are calculated.

## 2D Analysis

Tay and Zhu [1,2], carried out a parametric study on the effect of various geometric parameters on delamination in a rectangular TSSOP (Thin Shrink Small Outline Package) with outer package dimensions 9.7mm×4.4mm×1mm, pad dimensions 5.5mm×3mm ×0.125mm and die dimensions 1.80mm×1.39mm×0.28mm shown in Fig. 1. Two 2D finite element models were created with one sectioning along the length of the outline package (section A-A) as shown in Fig. 1, which will be called the “Long Side” and the other along the width of the package (section B-B) which will be called the “Short Side”. Fig. 2 shows a cross-section of the package.

4-node non-singular elements were used and the ERR and mode mixity,  $\psi$ , were calculated using the Virtual Crack Closure Method (VCCM) [5] and given in equations (1) to (3).

$$G_I = \frac{1}{2\Delta} \left[ Y^{FL1} (v^{DL1} - v^{DL1'}) \right] \quad (1)$$

$$G_{II} = \frac{1}{2\Delta} \left[ X^{FL1} (u^{DL1} - u^{DL1'}) \right] \quad (2)$$

$$\psi = \tan^{-1} \sqrt{\frac{G_{II}}{G_I}} \quad (3)$$

X, Y and Z refer to the nodal forces in the local  $x$ ,  $y$  and  $z$  directions, respectively, while  $u$ ,  $v$  and  $w$  refer to the displacements in the local  $x$ ,  $y$  and  $z$  directions. The superscripts FL1 etc. refers to the upper nodes and FL1' etc. refers to the lower nodes as depicted in Fig. 3. An initial delamination (interface crack) of 0.2 mm was assumed at the edge of the pad-encapsulant interface (Fig. 2). The results of the 2D fracture mechanics analysis by Tay and Zhu [1] are shown in Figs. 4-5. It can be seen that both ERR and  $\psi$  at the crack tip depend on  $b$  only and are independent of the size of the die,  $2d$ .

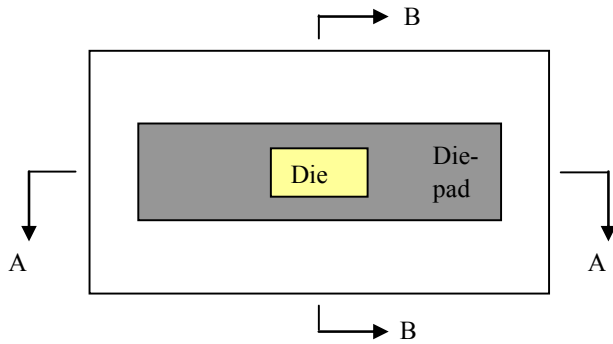


Fig. 1. Plan view of TSSOP Package

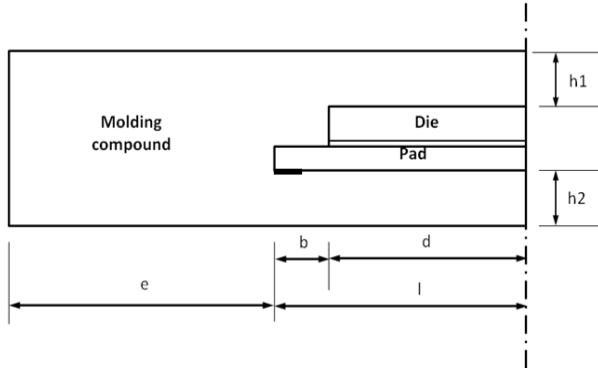


Fig. 2. Cross-sectional view of IC package under analysis.

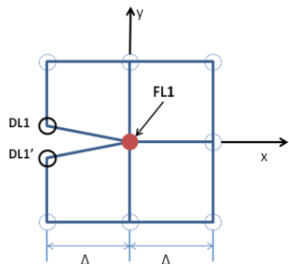


Fig. 3. 2D 4-noded element

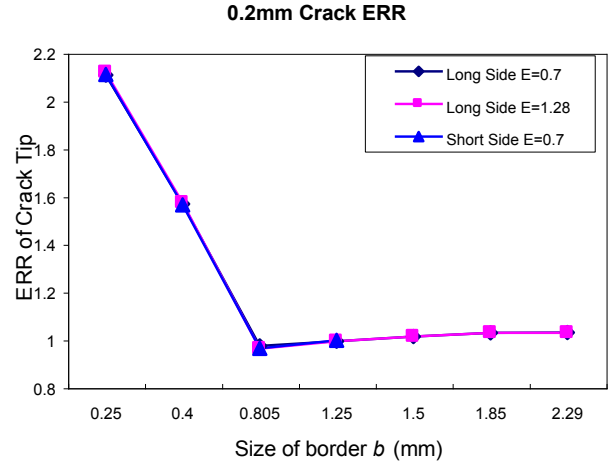


Fig. 4. Variation of ERR with  $b$  for crack length of 0.2 mm.

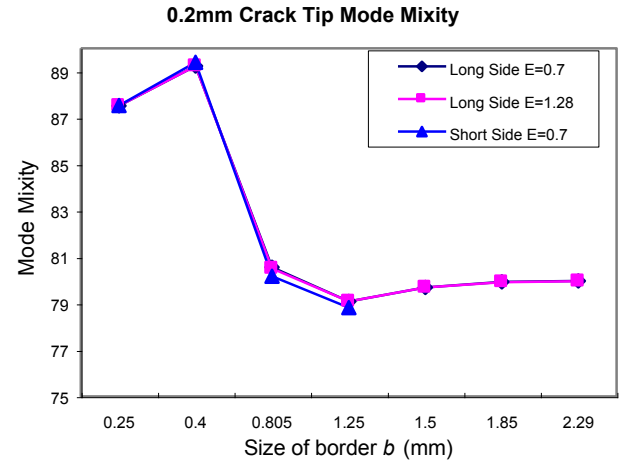


Fig. 5. Variation of  $\psi$  with  $b$  for crack length of 0.2 mm.

### 3D Analysis

For 3D analysis, the ERR for 20-node elements can be obtained from equations (3)-(5) [6]:

$$G_I = -\frac{1}{2t\Delta} \left[ \begin{aligned} &Z^{FL1} (w^{DL1} - w^{DL1'}) + Z^{FL2} (w^{DL2} - w^{DL2'}) \\ &+ Z^{FM1} (w^{DM1} - w^{DM1'}) \\ &+ Z^{FN1} (w^{DN1} - w^{DN1'}) + Z^{FN2} (w^{DN2} - w^{DN2'}) \end{aligned} \right] \quad (4)$$

$$G_{II} = -\frac{1}{2t\Delta} \left[ \begin{aligned} &X^{FL1} (u^{DL1} - u^{DL1'}) + X^{FL2} (u^{DL2} - u^{DL2'}) \\ &+ X^{FM1} (u^{DM1} - u^{DM1'}) \\ &+ X^{FN1} (u^{DN1} - u^{DN1'}) + X^{FN2} (u^{DN2} - u^{DN2'}) \end{aligned} \right] \quad (5)$$

$$G_{III} = -\frac{1}{2t\Delta} \left[ \begin{aligned} &Y^{FL1} (v^{DL1} - v^{DL1'}) + Y^{FL2} (v^{DL2} - v^{DL2'}) \\ &+ Y^{FM1} (v^{DM1} - v^{DM1'}) \\ &+ Y^{FN1} (v^{DN1} - v^{DN1'}) + Y^{FN2} (v^{DN2} - v^{DN2'}) \end{aligned} \right] \quad (6)$$

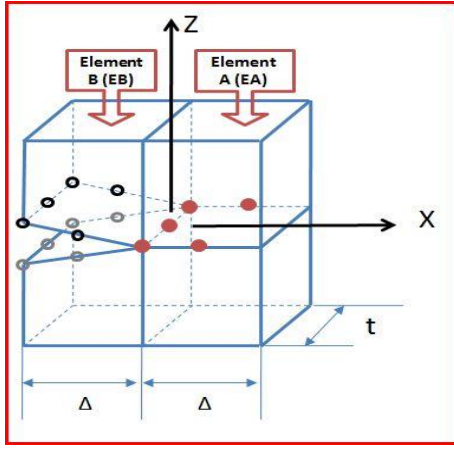


Fig. 6. 20-node solid element (3D View)

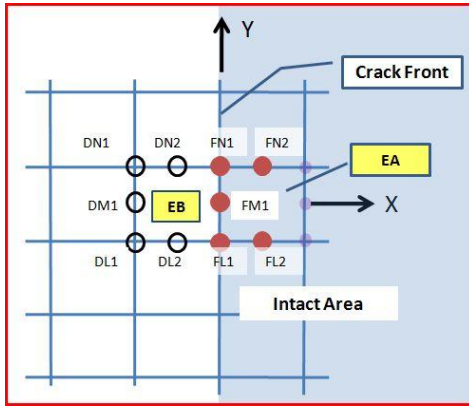


Fig. 7. 20-node solid element (top view) with lower nodes omitted for clarity

The mode mixity in this work is obtained using a Modified VCCM (MVCCM) developed by Hu and Tay [7] from which equations (7) to (16) are obtained.

$$\text{If } \delta u^{DL1} = u^{DL1} - u^{DL1'} < 0$$

$$\frac{K_{II}}{K_I} = \frac{-2A_{12}(1+R_0) + \sqrt{4A_{12}^2(1+R_0)^2 - 4(R_0A_2 - A_1)(R_0A_1 - A_2)}}{2(R_0A_2 - A_1)} \quad (7)$$

$$\text{If } \delta u^{DL1} = u^{DL1} - u^{DL1'} > 0$$

$$\frac{K_{II}}{K_I} = \frac{-2A_{12}(1+R_0) - \sqrt{4A_{12}^2(1+R_0)^2 - 4(R_0A_2 - A_1)(R_0A_1 - A_2)}}{2(R_0A_2 - A_1)} \quad (8)$$

where  $R_0 = G_{II}/G_I$  is the ratio of ERR which can be obtained from equations (4) to (6) and

$$A_1 = \frac{(c_1 + c_2)}{8 \cosh^2(\pi\epsilon)(1+4\epsilon^2)} \left[ \cos\left(2\epsilon \ln \frac{\Delta}{2a}\right) \left(\frac{1}{4} - \frac{67}{42}\epsilon^2\right) + \sin\left(2\epsilon \ln \frac{\Delta}{2a}\right) \left(\frac{17}{14}\epsilon - \frac{1}{3}\epsilon^3\right) + \left(\frac{1}{4} + \epsilon^2\right) \right] \quad (9)$$

$$A_2 = \frac{(c_1 + c_2)}{8 \cosh^2(\pi\epsilon)(1+4\epsilon^2)} \left[ \cos\left(2\epsilon \ln \frac{\Delta}{2a}\right) \left(-\frac{1}{4} + \frac{67}{42}\epsilon^2\right) + \sin\left(2\epsilon \ln \frac{\Delta}{2a}\right) \left(-\frac{17}{14}\epsilon + \frac{1}{3}\epsilon^3\right) + \left(\frac{1}{4} + \epsilon^2\right) \right] \quad (10)$$

$$2A_{12} = \frac{(c_1 + c_2)}{4 \cosh^2(\pi\epsilon)(1+4\epsilon^2)} \left[ \cos\left(2\epsilon \ln \frac{\Delta}{2a}\right) \left(\frac{17}{14}\epsilon - \frac{1}{3}\epsilon^3\right) + \sin\left(2\epsilon \ln \frac{\Delta}{2a}\right) \left(-\frac{1}{4} + \frac{67}{42}\epsilon^2\right) \right] \quad (11)$$

in which

$$c_1 = (\kappa_1 + 1)/\mu_1 \quad (12)$$

$$c_2 = (\kappa_2 + 1)/\mu_2 \quad (13)$$

$$\epsilon = \frac{1}{2\pi} \ln \left[ \left( \frac{\kappa_1}{\mu_1} + \frac{1}{\mu_2} \right) / \left( \frac{\kappa_2}{\mu_2} + \frac{1}{\mu_1} \right) \right] \quad (14)$$

$$\kappa = 3 - 4\nu \quad (\text{for plane strain}) \quad (15)$$

$$\mu = \frac{E}{2(1+\nu)} \quad (16)$$

where  $2a$  is the crack size,  $\mu$  is the shear modulus,  $E$  is the elastic modulus and  $\nu$  is the Poisson's ratio. The subscripts 1 and 2 refer to material 1 and material 2, respectively.

### Effect of Die Size

One interesting finding in 2D finite element linear fracture mechanics study is that the border size  $b$  (refer to Fig. 2) is the critical parameter influencing the ERR of a delamination of specified size located at the pad/encapsulant interface [1], and the die size  $d$  has negligible influence on the ERR. This suggests that as long as  $b$  is kept constant even though the die size increases, the risk of delamination propagation at the pad/encapsulant delamination remains the same. This work re-investigates this finding using 3D finite element models.

The dimensions of the packages (refer to Fig. 2) analysed using 3D linear fracture mechanics analysis are listed in Table 1.  $d$  and  $l$  are increased to 7.985mm and 8.95mm in package 2 and 11.485mm and 12.45mm in package 3 while keeping  $b$  the same as in package 1. 3D finite element models in which a corner delamination is assumed are analyzed. Three different shapes of the initial corner delamination, namely concave, convex and straight, are considered for each package studied. Here, a concave delamination refers to the case where the crack front bulges towards the corner of the pad, a convex delamination is the case where the crack front bulges towards the center, and a straight delamination is the case of having a straight crack front (refer to Figure 8).

Table 1 Geometric parameters of packages analyzed in 3D (all dimensions in mm)

|                  | $d$    | $b$   | $l$   | $e$  | $h1$  | $h2$ |
|------------------|--------|-------|-------|------|-------|------|
| <b>Package 1</b> | 4.485  | 0.965 | 5.45  | 8.55 | 1.345 | 1.5  |
| <b>Package 2</b> | 7.985  | 0.965 | 8.95  | 8.55 | 1.345 | 1.5  |
| <b>Package 3</b> | 11.485 | 0.965 | 12.45 | 8.55 | 1.345 | 1.5  |

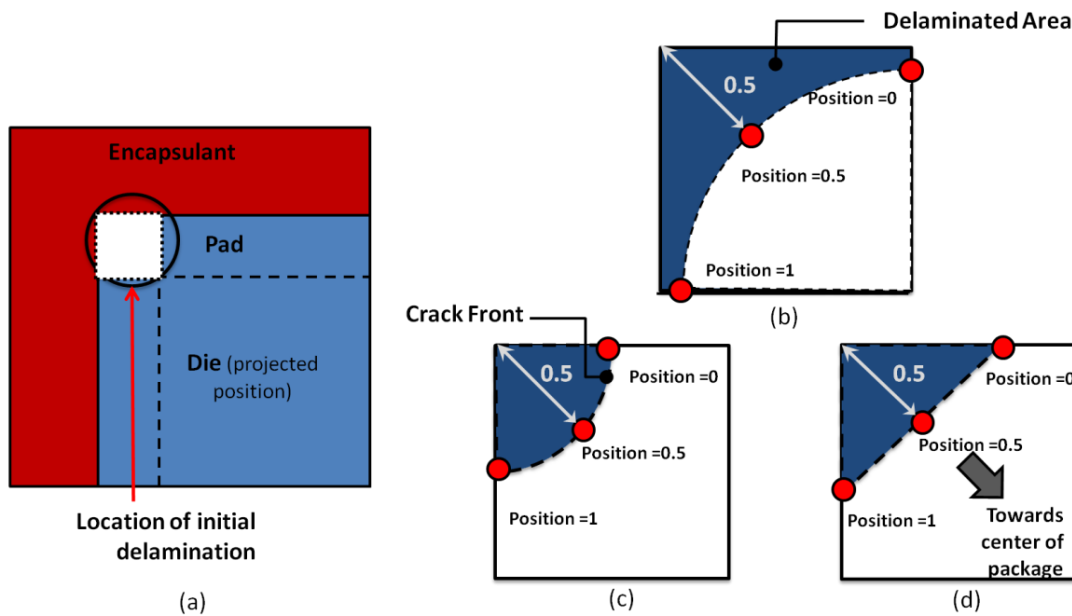


Fig. 8. (a) Illustration of the location of initial delamination (b) A convex initial delamination (c) A concave delamination (d) A straight delamination

## Results and Discussion

The variations of ERR and mode mixity along the crack front, from position 0 to 1 are plotted in Figures 9 to 15. Position 0 and 1 refer to the locations at the crack front while position 0.5 refers to the location at the mid-point of the crack front (Fig. 8).

From Figure 9 to Figure 11, it can be seen that no matter what the shape of the initial corner delamination, the ERR increases from Package 1 to Package 3, with an increase of as much as 37% (for concave delamination,) indicating that when the die size increases, the ERR increases even though the border size  $b$  is kept the same. The increase in ERR is observed at all the positions along the crack front and for the three different crack fronts analysed in this study. This finding is in contrast to the observation in Fig. 4 from the 2D analyses that changing the die size without changing  $b$  did not lead to significant changes in ERR. The reasons for such a difference in the trend were discussed earlier in the Introduction.

The variation of mode mixity with die size obtained from the 3D analyses are shown in Figures 12 to 14. The results

show that for the initial corner delaminations which are convex and straight, mode mixity does not vary with the die size but for a concave initial delamination, it does slightly, first decreasing then increasing. From Fig. 5, it can be seen that the mode mixity was predicted by the 2D analysis to be independent of the die size. Thus the trend on variation of mode mixity with die size predicted from the 2D analysis agrees with the 3D analysis for the convex and straight initial corner delaminations. However, it was argued in an earlier publication by the authors [8], that the most likely shape of initial delaminations is the concave one. This is because it gave an ERR and mode mixity which is practically constant along the entire crack front, which is what one would expect for the propagation of a crack front.

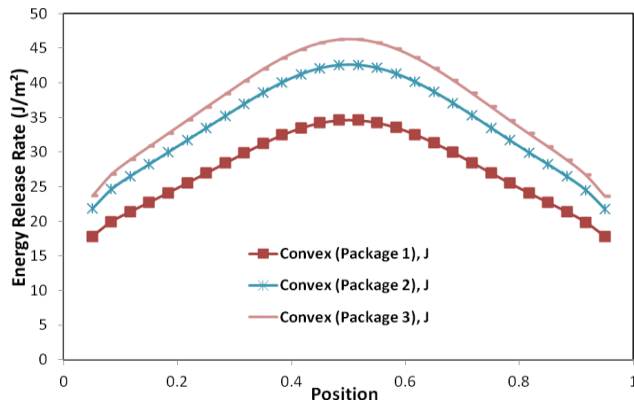


Fig. 9. Effect of  $d$  on ERR for a convex delamination

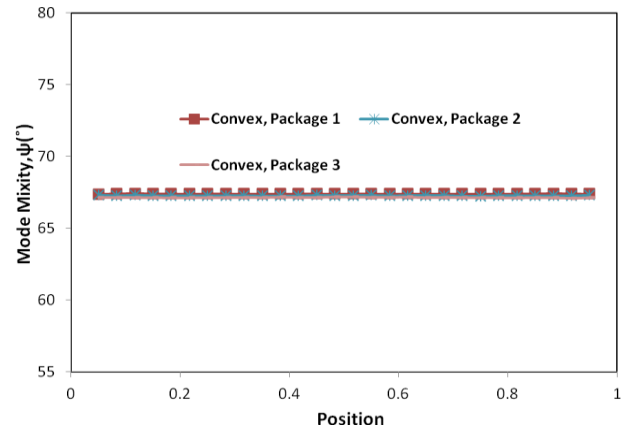


Fig. 12. Effect of  $d$  on mode mixity for a convex delamination

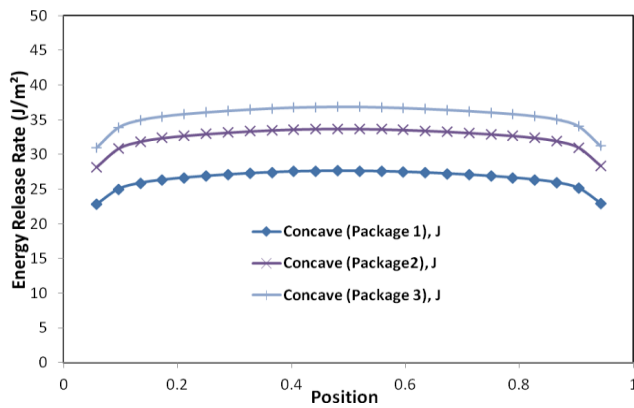


Fig. 10. Effect of  $d$  on ERR for a concave delamination

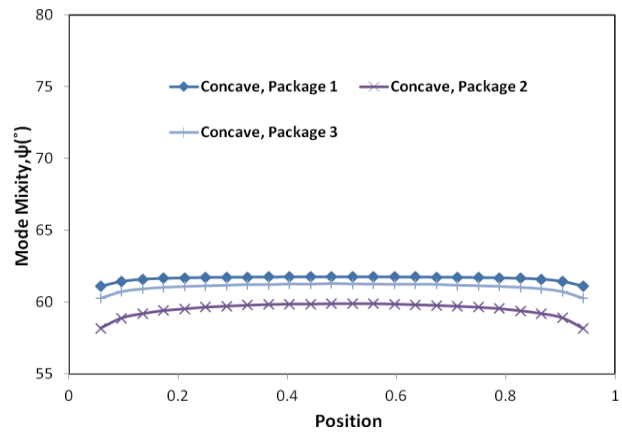


Fig. 13. Effect of  $d$  on mode mixity for a concave delamination

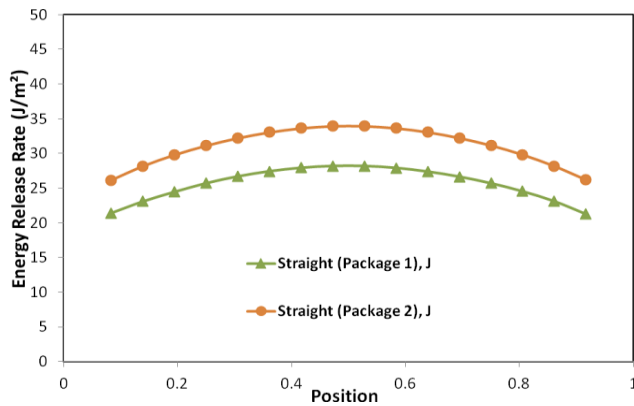


Fig. 11. Effect of  $d$  on ERR for a straight delamination

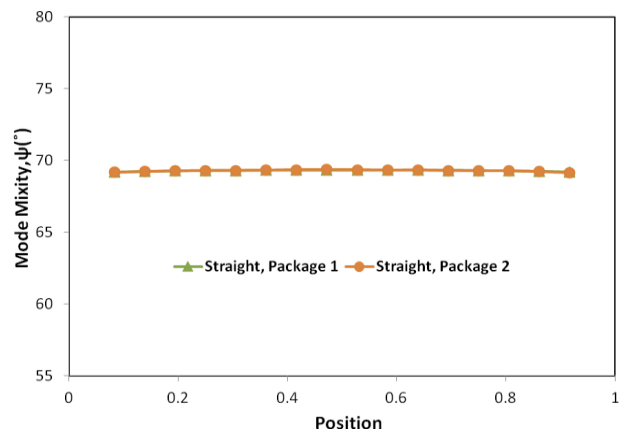


Fig. 14. Effect of  $d$  on mode mixity for a straight delamination

## Conclusion

Generally, increasing the die size and package dimensions  $d$  and  $l$  is likely to increase the probability of delamination

propagation since the ERR increases while mode mixity remains relatively unchanged. The size of the die and pad (as manifested in parameters  $d$  and  $l$ ) has significant influence on the ERR. From the parametric studies, it has been shown that the trends predicted by the 2D and 3D analyses differ. A 2D parametric study suggests that the ERR is independent of die size while a 3D parametric study of numerous types of corner delaminations suggest that ERR will increase with die size.

## References

- [1] Tay, A. A. O., and Zhu, H., 2001, "Fracture mechanics analysis of the effect of geometry on delaminations in rectangular IC packages," Electronic Components and Technology Conference, 2001. Proceedings., 51st, pp. 620-623.
- [2] Tay, A. A. O., and Zhu, H., 2002, "A numerical study of the effect of die, die pad and die attach thicknesses on thin plastic packages," Electronic Components and Technology Conference, 2002. Proceedings. 52nd, pp. 199-204
- [3] Xie, B., Xunqing, S., and Xuejun, F., 2007, "Sensitivity Investigation of Substrate Thickness and Reflow Profile on Wafer Level Film Failures in 3D Chip Scale Packages by Finite Element Modeling," Electronic Components and Technology Conference, 2007. ECTC '07. Proceedings. 57th, pp. 242-248.
- [4] Yong, L., Irving, S., Rioux, M., Schoenberg, A. J., and Chong, D., 2002, "Die attach delamination characterization modeling for SOIC package," Electronic Components and Technology Conference, 2002. Proceedings. 52nd, pp. 839-846.
- [5] Raju, I. S., 1987, "Calculation of Strain-Energy Release Rates with Higher Order and Singular Finite Elements," Engineering Fracture Mechanics, 28(3), pp. 251-274.
- [6] Raju, I. S., Sistla, R., and Krishnamurthy, T., 1996, "Fracture mechanics analyses for skin-stiffener debonding," Engineering Fracture Mechanics, 54(3), pp. 371-385.
- [7] Hu, G., and Tay, A. A. O., 2005, "Application of modified virtual crack closure method on delamination analysis in a plastic IC package during lead-free solder reflow," 7th Electronics Packaging Technology Conference, EPTC 2005Singapore, Singapore, pp. 555-560.
- [8] Siow Ling, H., and Tay, A. A. O., 2009, "A numerical study of 3D interfacial delamination in PQFP packages," Electronics Packaging Technology Conference, 2009. EPTC '09. 11th, pp. 957-963.