Effects of voids on postbuckling delamination growth in unidirectional composites

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A B S T R A C T

This work examines the effects of manufacturing induced voids on the postbuckling behavior of delaminated unidirectional composites. In the finite element model developed, a through-width delamination is introduced close to one surface of a flat panel, and a void is placed in the delamination plane ahead of each delamination front. The panel is subjected to compression in the fiber direction. The postbuckling delamination growth is studied by calculating the strain energy release rate (SERR) using the virtual crack closure technique. Local stress analyses of the region near the delamination front are also performed to further investigate the void effects. It is found that although the presence of void does not significantly alter the postbuckling transverse displacement of the delaminated panel, the induced stress perturbation by the void affects the SERR. The Mode II SERR as well as the total SERR increase depending on the size of the void and its distance from the delamination front. Since the Mode I SERR shows non-monotonic behavior with the applied load, the effects of voids are studied on its maximum value.

1. Introduction

Composite materials continue to be applied in a wide range of load bearing structures due to their attractive properties. Many of these structures have a laminated construction, which is prone to local delamination caused by impact, manufacturing defects or discontinuities, leading to degradation of structural performance (Garg, 1988). For a delaminated structure subjected to in-plane compression, the delamination region may buckle out of the plane when the compressive load reaches a critical value and an increase in this load can cause further growth of delamination resulting in final failure.

Chai et al. (1981) were the first to develop a one-dimensional model to study the postbuckling deformation of laminated plates. Later, Kyoung and Kim (1995) included transverse shear deformation in the analysis and found the dependence of buckling load on delamination configuration. Whitcomb (1981, 1984) used two-dimensional finite element analysis to study the postbuckling deformation and the influence of delamination configuration. Besides such analytical and numerical investigations, some experiments were also conducted to characterize the postbuckling behavior (Kardomateas, 1990). Single versus multiple delaminations have also been studied, and depending on the configuration of multiple delaminations, significant differences in the buckling behavior were found (Kutlu and Chang, 1995; Lim and Parsons, 1993; Suemasu, 1993). However, for relatively long delamination near the surface, it was found that the buckling behavior of multiple delaminations was almost the same as that of a single delamination (Hwang and Liu, 2001).

In composite materials, voids inevitably exist induced by manufacturing. Many experiments have shown that mechanical properties such as interlaminar shear strength, fatigue resistance and compressive strength decrease with increasing void content (Bowles and Frimpong, 1992; de Almeida and Neto, 1994; Ghiorse, 1993; Judd and Wright, 1978; Suarez et al., 1993; Wisnom et al., 1996). In spite of the overwhelming evidence, relatively few models are available to analyze the effects of voids. Based on the beam theory, Hagstrang et al. (2005) found that the presence of voids had a detrimental effect on the flexural modulus and strength. Huang and Talreja (2005) proposed a computational model to assess the effect of void geometry on elastic properties of unidirectional composites and showed that the voids have much larger influence on reducing the out-of-plane properties than the in-plane ones. Recent studies (Lambert et al., 2012; Ricotta et al., 2008) have indicated that the void content by itself is inadequate to explain the effect of voids. Instead, factors such as size and shape of voids, as well as their location, must be considered. In fact the effect of voids and other defects such as fiber waviness and irregular fiber distribution in initiating damage and the interaction...
between damage and defects have prompted a new field called "defect damage mechanics" (Talreja, 2009) for assessing the effects of defects on composite performance.

This paper presents results of a parametrical study of the effects of voids on the postbuckling behavior of a unidirectional composite panel with a through-width delamination. Recent investigations on voids (e.g., Lambert et al., 2012) have indicated that extremes in the distribution of voids and their placement in critical areas are important factors in affecting the composite performance. As a result, instead of studying distributed voids throughout the volume and their averages, we choose to focus here on the critical effects of the voids in terms of their size and placement. Thus we place one void each ahead of the two fronts of the delamination lying parallel and close to the surface of the panel loaded in axial compression and in the parametric study vary the size of the voids and their distance from the delamination front. For a single delamination, local buckling usually occurs at a lower load than global buckling (Wang and Zhang, 2009). The effect of voids on strain energy release rate (SERR, denoted G) is calculated to represent the driving force for delamination growth. The local stress field near delamination front is also studied in order to further understand the effects of voids.

2. Model description

We model the problem as a 2-D composite plate with fibers in the longitudinal direction containing a single through-width delamination close to one of the plate surfaces. For comparison purposes, the material properties taken are those used in Whitcomb (1984) (Table 1). The plate is assumed to be clamped at both ends and loaded in axial compression. The dimensions used in the model are labeled in the 2-D section of the plate in Fig. 1, and are as follows. Plate length \( 2L = 100 \text{ mm} \), thickness \( h = 2.0 \text{ mm} \) and width (not shown in Fig 2) is assumed to be 20 mm; delamination length \( 2a = 30 \text{ mm} \), and the shorter distance of delamination from the plate surface \( t = 0.25 \text{ mm} \). For the selected dimensions of the plate and delamination, and the distance of delamination from the surface, local buckling is expected to occur under axial compression.

To study the effect of manufacturing induced voids on the local buckling of the plate, one void is placed ahead of each delamination front in the delamination plane, as the position of the void in this plane is expected to influence the stress field at the delamination front more than positions of the same void in other locations for a given distance from the delamination front. The distance of the center of void from the delamination front, denoted by \( d \), is used as a variable. Although in reality the voids have a 3-D geometry, in the 2-D finite element (FE) model used here, the voids are modeled as a through-width cutout region parallel to the delamination front. Images of voids situated in interfaces between plies in unidirectional composites manufactured from prepregs are shown on Fig. 2. As described in Huang and Talreja (2005), most of these voids have elongated cylindrical, cigar-shaped geometry running along the fiber direction. Hence, in our model, for simplicity and to adapt the void shape to the 2-D case, the section of the void parallel to the fiber direction is modeled as a rectangle with semi-circular caps at both ends, as illustrated in Fig. 1. The void dimensions \( L_v \) and \( h_v \) are depicted in Fig. 1.

A 2-D geometrically nonlinear FE analysis was performed using the commercial software ABAQUS. For the model shown in Fig. 1, Because of the symmetry, half of the plate was modeled and symmetry boundary conditions were imposed on the plane \( X = 0 \). At the bottom of the plate, displacement along the \( Y \)-direction was constrained in order to induce local buckling. At the end of the plate, \( L = 50 \text{ mm} \), uniform axial displacement was applied to simulate the compressive load. Eight node plane strain quadrilateral elements were used near the delamination front, and reduced integration scheme was implemented in order to improve the performance of the 2-D elements. As recommended for the virtual crack closure technique (VCCT), the region near delamination front was modeled by symmetrically regular shaped elements of uniform size, as indicated in the FE mesh shown in Fig. 3, and the smallest element size was chosen as \( e = 0.0125 \text{ mm} \).

It is noted that we did not impose the contact constraint in the model for the following reason. As described in Whitcomb (1981) for near-surface delamination, the competitive interaction between the delamination front opening and closing moments, caused respectively by the increase of lateral deflection and the eccentricity in load path measured from the initial to the buckled configuration, leads to the delamination front opening first and then closing locally with the increase of the applied load. This results in the non-monotonic variation in \( G_1 \) (to be shown later). Since contact constraint was not imposed in the model, this would result in potential delamination face overlap in the FE analysis when the delamination front is closing. However, it was found that the maximum \( G_1 \) was reached while delamination front was still open and thus there is no contact between delamination faces at that point. After reaching the \( G_{\text{max}} \), if the delamination front starts to close locally with increasing applied load and delamination face

<table>
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<th>Table 1</th>
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<td>Elastic material properties (Whitcomb, 1984).</td>
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<td>( E_{11} ) (GPa)</td>
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Fig. 1. Schematic illustration of the model.
penetration occurs, the total $G$ value given by the non-contact analysis does not change significantly from the contact analysis value (Whitcomb, 1984), and can therefore be used as a good approximation.

A postbuckling analysis for the case of delamination without void was also performed. FE model for the no-void case was basically the same as that for the void case. FE results of both cases were then compared in order to demonstrate the effects of voids.

3. Model validation

The validation of the FE model was done for the no-void case, as described below.

In the non-linear postbuckling analysis, a small sine-shaped transverse displacement (or imperfection) based on the linear buckling analysis is usually introduced in order to initiate buckling. Here, three different trial values of the initial transverse displacement are chosen ($\delta H = 0.25\%$, $0.5\%$, and $2.5\%$) in order to assess its effect on $G$. The calculated mode I and mode II components of $G$, denoted $G_I$ and $G_{II}$, respectively, are plotted in Fig. 4. As seen in Fig. 4, in each case, $G_I$ increases first and then starts to decrease after applied load reaches around 4 KN, while $G_{II}$ increases monotonically with increasing applied load. Meanwhile, $G_I$ value is affected only slightly for $\delta H = 0.5\%$ or less, while $G_{II}$ value shows insensitivity to all three values of $\delta$. Thus, $\delta H = 0.5\%$ is selected for the current study.

The calculated values of $G$ from the FE model were then compared with the solution for “thick-column” (or “thick-beam”) model proposed by Chai et al. (1981). In that paper, “thin-film”, “thick-column” and “general” models were developed and compared. The “thin-film” model assumes a thin delamination plate with infinitely thick unbuckled part, and solution for $G$ is then obtained by treating the buckled plate by a 1-D beam theory. The “general” model is, however, more complex because of the finite thickness of the unbuckled part, and in order to apply a 1-D beam theory, the entire plate is divided into sections, each assumed as a beam column. The plate is assumed to undergo cylindrical bending, and compatibility and equilibrium are enforced at interfaces between sections. The solution to $G$ is evaluated numerically, as a closed form solution is not possible. As noted by Chai et al. (1981), the “general” case is significantly simplified if the thickness of delaminated plate is small compared to unbuckled plate, and in order to apply a 1-D beam theory, the entire plate is divided into sections, each assumed as a beam column. The plate is assumed to undergo cylindrical bending, and compatibility and equilibrium are enforced at interfaces between sections. The solution to $G$ is evaluated numerically, as a closed form solution is not possible. As noted by Chai et al. (1981), the “general” case is significantly simplified if the thickness of delaminated plate is small compared to unbuckled plate, and in order to apply a 1-D beam theory, the entire plate is divided into sections, each assumed as a beam column.
local buckling, bending of the unbuckled sections was suppressed, resulting in the “thick-column” model. Therefore, the solution to $G$ corresponding to the “thick column” model was used to validate our FE model. The expression for $G$ is reproduced below as Eq. (1), where it is denoted as $G_T$. In Eq. (1), unknown variables $e_0$, $e_{cr}$ and $e_L$ are loading strain, buckling strain of delamination plate and buckling strain of the whole plate, respectively. It is noted that the $G_I$ and $G_{II}$ values obtained from the VCCT are added together for comparison with this value, as the “thick column” model provides only the total $G$ value. As seen in Fig. 5, a good agreement between the FE model and this value is found, validating thereby the accuracy of the FE model used here.

$$
G_T = \frac{N^4H^2(1-H^2)\left(\frac{1}{2H} - \frac{1}{H^2}\right)\left(1 + \frac{3}{2}\frac{H^2}{H^2 - 1}\right)}{(1-H^2)^2}\left(18(1 - \frac{H}{H^2})^2\right)
$$

$$
N = E_1H^2(2L)^4(1 - v_{12})^{-1}
$$

$$
e_{cr} = \frac{\rho_1}{(1 - v_{12})\left(\frac{L}{2}\right)^2}, \quad e_L = \frac{\rho_1}{(1 - v_{12})\left(\frac{H}{2}\right)^2}
$$

4. Results and discussion

Having validated the FE model, we now proceed to examine the effects of voids on $G$ and buckling displacement associated with the

Fig. 4. Effect of initial transverse displacement on calculated $G$ values (a) $G_I$ and (b) $G_{II}$.

Fig. 5. Comparison of $G_T$ results given by the FE model and the analytical model.

Fig. 6. Effect of void on $G_I$.

Fig. 7. Effect of void on $G_{II}$. 

Fig. 5. Comparison of $G_T$ results given by the FE model and the analytical model.
delamination. Figs. 6 and 7 show the effect of void on each component of $G$ as well as the total $G$ against the applied load $P$ normalized by a reference value $P_{cr}$, the applied load when buckling occurs. Void dimensions $L_v = 520 \mu m$ and $h_v = 20 \mu m$ were chosen in order to represent the commonly found voids in unidirectional composites manufactured using pre-pregs in an autoclave process (Huang and Talreja, 2005). The distance between delamination front and void center was taken as $d = 0.40 \ mm$.

From Fig. 6 it can be seen that $G_I$ increases first and then decreases, which as described previously is attributed to the competitive interaction between the crack front opening and closing moments. At a certain applied load, which depends on the geometry of the delamination and material properties of the structure, $G_I$ starts to decrease as delamination front starts to close.

As seen in Fig. 6, in the opening phase of the delamination front, i.e. before $G_I$ reaches its maximum value, the presence of void decreases $G_I$. The effect of void on $G_I$ becomes more significant during the closing tendency of the delamination, when the presence of void enhances $G_I$. However, this effect is of no practical interest since failure from delamination will occur at or before reaching the maximum $G_I$ value. Unlike $G_I$, the presence of void increases $G_{II}$ regardless of whether delamination front is opening or closing. Meanwhile, note that for the same $P$, the $G_{II}$ value is much larger than $G_I$, which is due to closeness of the delamination to the plate surface. As a result, $G_T$ is dominated by $G_{II}$, and the effect of void on $G_T$ is expected to follow the same trend as that for $G_{II}$ and thus is excluded in the following discussion. It should be noted that the calculated results are for the loads less than that required to completely close the delamination front.

Fig. 8 shows the transverse displacement of the buckled delamination for the no-void and void cases under three different applied loads. Due to symmetry, the displacement profile of one-half of the
delamination is shown. As seen in the figure, there is no significant effect of the presence of void on the buckling displacement.

In Fig. 9 the postbuckling displacement of the region close to the delamination front is plotted for the no-void and void cases at the three applied loads. Comparing Fig. 8 and Fig. 9 it can be seen that while away from the delamination front the transverse displacement increases monotonically with the applied load, it does not do so very close to the delamination front. There it increases with the applied load until about $P/P_{cr} = 2.35$, i.e. until $G_I$ attains its maximum (see Fig. 5), and then decreases following the trend in $G_I$.

It is clear that the presence of void ahead of the delamination front induces a stress perturbation, which by interacting with the stress field near the delamination front affects its $G$ values. In an effort to gain insight into the observed trends in the effects on $G_I$ and $G_W$, we calculate the stresses on the delamination plane ahead of the delamination front. Since both the normal stress ($\sigma_{22}$) and the shear stress ($\sigma_{12}$) on this plane are singular at the delamination front, we calculate their values slightly away from the delamination front. The normal and interlaminar shear stresses are plotted in Fig. 10 and Fig. 11, respectively, at three applied loads, $P/P_{cr} = 1.35, 2.35$, and $3.88$ for the no-void and void cases.

As seen in Fig. 10, with the presence of void, normal stress closer to the delamination front is slightly lower in the opening phase ($P/P_{cr} = 1.35$ and $2.35$) and then becomes higher during the closing of the delamination front ($P/P_{cr} = 3.88$). In Fig. 11, interlaminar shear stress closer to the delamination front is always higher in the void case irrespective of the opening and closing of the delamination front. Both results demonstrate the same trend as that shown in Fig. 5 and Fig. 6. As a result, it could be suggested that the presence of void causes a stress perturbation near the delamination front and thus affects the corresponding $G$ components accordingly.

5. Parametric studies

5.1. Effects of void size and location

The effects of void size and void location are studied to gain further insight into the delamination failure. For $G_I$, only the values in the opening phase of the delamination front matter and among these the maximum values are the most critical. Therefore, in both void and no-void cases, the maximum values of $G_I$ were calculated and compared to determine the void effect on $G_I$. The effects on $G_W$ are also calculated and it is noted that $G_I$ follows the same trend as $G_W$.

Figs. 12 and 13 show the influence of void size on the calculated $G$ values, with void’s height and location kept constant. From these figures it can be seen that the maximum $G_I$ value decreases with increasing void size while all values of $G_W$ increase with increasing void size.

The effects of void location with respect to the delamination front are shown in Figs. 14 and 15. As indicated in Fig. 14, the effect of void position on the maximum $G_I$ value is not monotonic. The void tends to decrease this value for a short distance of $d \sim 0.6$ mm, beyond which the effect diminishes and the maximum $G_I$ approaches the no-void value. $G_W$, on the other hand, increases monotonically as the void approaches the delamination front, and this effect dies out as the void moves away, as shown in Fig. 15.

5.2. Effects of stiffness properties

In the study of the void effects presented above, we used typical properties of a graphite/epoxy composite (Table 1), also since these properties were used in a previous study of postbuckling without voids (Whitcomb, 1984). It would be of interest to determine how the void effects manifest themselves for other graphite/epoxy composites and for other material systems such as glass/epoxy. For this reason we present below the effects on $G$ of variations in the longitudinal modulus $E_1$, the transverse modulus $E_2$, and the stiffness ratio $E_1/E_2$. The void geometry and its position in the interface are kept constant.
Fig. 16 plots the computed maximum $G_I$ values in the void case against the stiffness ratio. The upper curve in the figure is for the case of constant longitudinal stiffness, while the lower curve shows variation when the transverse modulus is kept fixed. As can be seen, the maximum $G_I$ depends strongly on the longitudinal modulus, while it barely changes with the transverse modulus. Similar results are found for $G_{II}$. From Figs. 17 and 18 it is seen that in the void case (results displayed by solid symbols), change of $E_1/E_2$ ratio has little effect on $G_{II}$ with constant $E_1$ (Fig. 17) while it increases with increasing $E_1/E_2$ ratio in the case of constant $E_2$ (Fig. 18).

It is to be noted that the $G$ values (both $G_I$ and $G_{II}$) depend strongly on $E_1$ irrespective of voids. The presence of voids brings about additional changes in $G$. These changes on $G_{II}$ are illustrated in Figs. 17 and 18. For the effects on the maximum $G_I$ we plot in Fig. 19 its ratio with respect to the no-void value against $E_1/E_2$. As can be seen, while the strong dependency of the maximum $G_I$ on $E_1$ is maintained, the voids either reduce or increase this value. The non-monotonic effect of stiffness ratio on the maximum $G_I$ for one fixed $E_1$ and $E_2$ case was discussed above (Fig. 16). Fig. 19 shows, however, that increasing stiffness ratio tends to increase the effect of voids on the maximum $G_I$. 
5.3. Effect of delaminated plate thickness

At this point we have a good understanding of the effects of void on SERR, especially on $G_{II}$. Contrary to $G_{II}$, the effects of void on $G_{I}$ are more complex. Since the delaminated plate thickness (distance between the delamination and the surface) $t = 0.25$ mm considered above produces small $G_{I}$, it would be interesting to study the case where $G_{I}$ is more significant during a mixed-mode delamination. Previous studies (Whitcomb, 1981) have shown that trends for $G_{I}$ and $G_{II}$ with respect to applied load are similar in different delaminated plate thicknesses while maximum value of $G_{I}$ increases as thickness increases. As a result, a further study was conducted here to investigate the void effect on $G_{I}$ and $G_{II}$ in thicker delaminated plate in the local buckling range. The FE model is the same as previous described except for the difference of $t$.

As shown in Fig. 20, with the increase of $t$, the presence of void increases $G_{I}$ more with thicker delaminated plate. From Fig. 21, it is seen that the presence of void increases $G_{II}$ in all cases. However, despite the large difference of $G_{II}$ values in different $t$ cases, it is found that the void effect on $G_{II}$ increases only slightly as $t$ increases, indicating that $G_{II}$ is less sensitive than $G_{I}$ with respect to the delaminated plate thickness. Finally, based on what we have found, it would be expected that a delamination would grow more
easily in a thicker delaminated plate than a thinner one during local buckling in the presence of voids.

6. Conclusions

A study has been performed to examine the effect of a single void ahead of the delamination front on the postbuckling behavior of a unidirectional composite plate under axial compression. The FE model, validated against an analytical model, was used to evaluate the values of $G$ and to perform the stress field analysis near the delamination front. The stresses on the delamination plane ahead of the delamination front were found to be consistent with the calculated trends in $G_I$ and $G_{II}$. Parametric studies were performed to investigate the effects of the void geometry and position, and the elastic properties of the composite. Following conclusions from these studies can be drawn.

a. The presence of void shows negligible effect on the buckling displacement of the part containing delamination.

b. The effect of void on $G_I$ shows a complex trend. In the opening phase of the delamination front, until $G_I$ attains its maximum value, different size and location of the void have different effects on $G_I$, and depending on the composite stiffness ratio and thickness of the delaminated part of the plate, the presence of void may decrease or increase the maximum $G_I$.

c. In the presence of voids, $G_{II}$ increases with increasing void size and with decreasing distance from the delamination front.

d. With all other parameters the same, the presence of voids is likely to be more detrimental for a structure undergoing local buckling with thicker delaminated plate.

The itemized conclusions stated above are a summary of the results of the mechanics analyses presented here. The important implication for applications to composite structures is that manufacturing induced defects such as voids influence the structural integrity, here more specifically the unstable growth of post-buckling delamination. Further, the results illustrate that the size, shape and position of the voids have specific influence that cannot be properly captured in the void volume fraction. Thus placing a threshold on the void volume fraction as a acceptance/rejection criterion is inadequate.

References


