EFFECTS OF VOIDS ON DELAMINATION GROWTH IN COMPOSITE LAMINATES UNDER COMPRESSION

A Thesis

by

LINQI ZHUANG

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Approved by:

Chair of Committee,	Ramesh Talreja
Committee Members,	Junuthula N.Reddy
	John Whitcomb
	Vikram Kinra
Head of Department,	Rodney Bowersox

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ABSTRACT

Polymer matrix composites are widely used as structural components in the aerospace industry and wind turbine industry etc. to take advantage of their unique mechanical properties and weight saving ability. Although there have been considerable developments in analyzing delamination growth and effects of voids on certain mechanical properties of composites, none of the present literatures investigates the effects of voids on delamination growth under compression.

In this research, a parametric study is performed to investigate the effects of voids on delamination growth in composite laminates under compression. In composite structures, delamination would be created by eccentricities in structural load path, structural discontinuities, and during manufacturing and maintenance processes. Also, the service damage such as the impact of foreign objects may also result in delamination. In the Finite Element model developed, a through-width surface delamination is assumed, and void is placed in critical locations ahead of crack tip. Strain Energy Release Rate (SERR) is calculated by the Virtual Crack Closure Technique (VCCT) in order to study the delamination growth. It is found that the delamination front experiences a mixed-mode delamination behavior when local out-of-plane buckling occurs. During the loading, Mode II SERR increases monotonically while Mode I SERR increases first and then decreases as the delamination front starts to close. Meanwhile, Mode II SERR is found to be much larger than the Mode I component. The presence of void does not significantly alter the transverse displacement of the delaminated part.

However, the presence of void increases the Mode II SERR, as well as the total SERR, and this increase depends on the size and location of void. For Mode I SERR, the effect of void is not that prominent.

To my beloved uncle

ACKNOWLEDGEMENTS

Back to 2010, when I was still a senior college student in China, I got a chance to know composites and to work on my first composite project. However, I was confused by the fact that we treat the entire composite specimen as a perfect state material while it is difficult to find a "perfect" state material in reality. I was wondering what would happen if we admit that composites are not perfect and consider flaws when we analyze them until I got a chance to read the paper "Defect damage mechanics: broader strategy for performance evaluation of composites" written by Dr.Talreja, and he kindly answered all my questions. Half a year later, I was sitting in the classroom of Texas A&M University and had the privilege to have him as my advisor.

I would like to take this opportunity to thank Dr. Talreja for bringing me to the world of composites research, and for his patience and sincere advice and guidance during my MS studies. I am lucky to be able to explore what fascinates me the most and to have an incredible teacher standing behind me.

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Finally, I would like to express my thanks and gratitude to all my family members, especially the best parents of the world, my mother and father, for their encouragement and unconditional love. It has been an emotional year for the family since a deadly car accident took the life of my beloved uncle a year ago. I just hope this thesis could ease the pain and bring back the joy as before.

NOMENCLATURE

ILSS	Interlaminar Shear Strength
FE	Finite Element
SERR	Strain Energy Release Rate
VCCT	Virtual Crack Closure Technique
DCB	Double Cantilever Beam

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CHAPTER I

INTRODUCTION

Polymer matrix composites are widely used as structural components in the aerospace industry and wind turbine industry etc. to take advantage of their unique mechanical properties and weight saving ability. Inspired by the concept of "defect damage mechanics"[1], the purpose of this research is to study the effects of voids parametrically, which are one of the most commonly observed manufacturing induced defects on the delaminated composites under compressive loading.

Extensive studies have been conducted on the delamination growth in composite laminates, however, as to the best of the author's knowledge, there is not any existing paper concerning about the effects of voids on the delamination growth in composites under compression. As a result, this research work would enhance the understanding of the effects of manufacturing induced defects especially voids and serve as a valuable guideline for engineers to evaluate the performance of delaminated composite structure components sustaining compressive load during service, which would help the development of designing more advance composite structures. Meanwhile, since the manufacturing process constitutes the most of cost of composite structures, by assessing the effect of voids we can also reach a trade-off between manufacturing cost and structure performance, we are able to reduce materials waste and contribute to a sustainable development of our society in the long-term.

A. Motivation

1. Get to know defect damage mechanics

Any innovation of structural design methodology is heavily dependent on the compatibility of structure durability analysis. Damage mechanics is playing a tremendously important role in component durability analysis as illustrated on Fig.1. However, the procedure described above does not incorporate manufacturing induced defects in it. Such defects would affect both initiation, evolution of damage events and then inevitably affect the critical state for final failure, which have been proven by many studies experimentally or analytically [2-8]. Since different defects would largely depend on the manufacturing process, and costs of manufacturing components constitute the majority part of products overall cost, a close link between structural performance evaluation and manufacturing process should be connected, and this concept is described in detail on Fig.2. The defect damage mechanics could be incorporated in the performance evaluation process as one of the analysis step, once the information of defects is obtained from previous manufacturing and material characterization process, the effects of certain manufacturing induced defects could be investigated and then combining with tradition structural durability analysis in the cost effectiveness assessment, a tradeoff between manufacturing cost and components performance could be achieved by adjusting defects to design requirement until the cost is minimized.

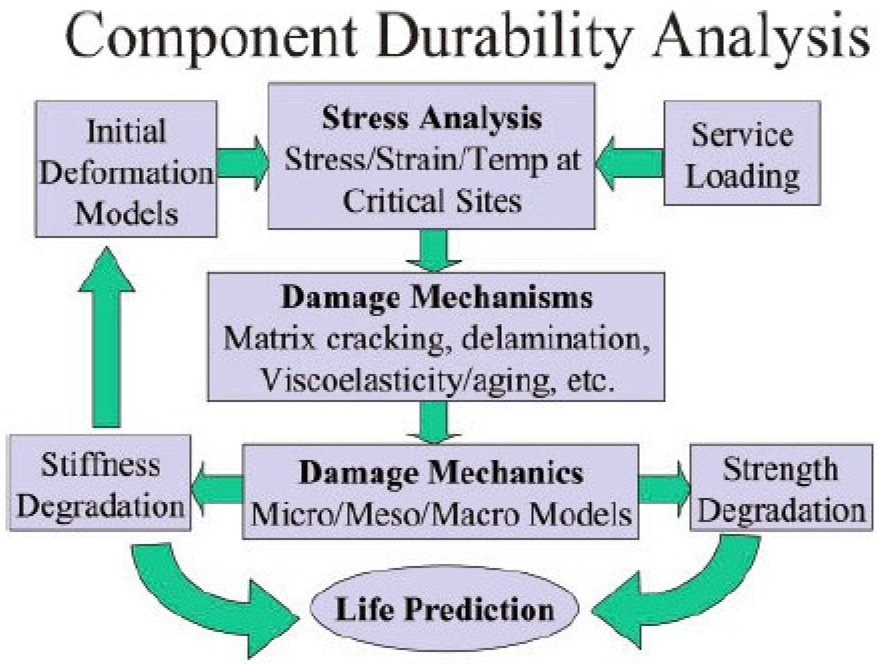


Fig. 1. Illustration of damage mechanics for Component Durability Analysis [1].

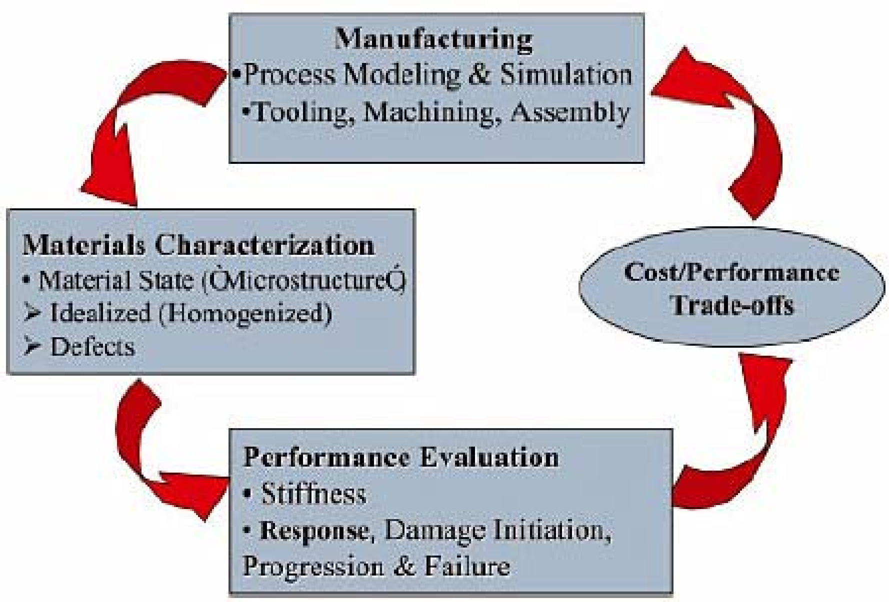


Fig. 2. Iterative process of cost effect manufacturing [1].

2. Delamination and its post-buckling behavior under compression

Polymer matrix composites have presented attractive advantages as structural components due to their unique mechanical properties and weight saving ability. When a load is applied to the laminated composite structures, damage may initiate and propagate in various failure modes, among which delamination is perhaps one of the most commonly observed damage modes due to laminated nature of composite structures.

Delamination may result from interlaminar stresses which would be created by eccentricities in structural load path, structural discontinuity. Some of the common design details that would result in discontinuities in the load path which would give rise to interlaminar stresses are show on Fig.3, these are (1) straight or (2) curved (near holes) free edges, (3) ply terminations or ply drop for tapering the thickness, (4) bonded or co-cured joints, (5) a bolted joint, and (6) a cracked lap shear specimen [9]. In all these cases, out-of plane stress would occur near these discontinuities even the remote loading is applied. Also, delamination may occur due to service damage such as the impact from foreign objects or occur during manufacturing and maintenance process.

For delaminated composite structures subjected to compressive loading, e.g. in plane compression or bending, once the compression load exceeds a critical value, the delamination region would buckle, and upper and lower part of this region would separate from each other in the post-buckling state. In the post-buckling state, the delaminated or debonding part experiences both opening and sliding action, which, if sufficiently severe, may initiate the delamination growth and compressive failure of structures.

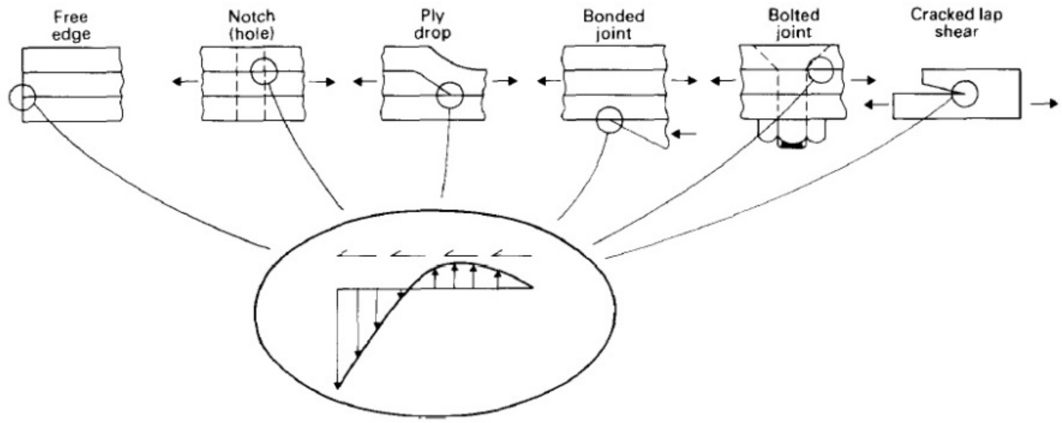


Fig. 3. Sources of out-of-plane stresses from load path discontinuities [9].

Chai et al [10] developed a one-dimensional analytical model to study the delamination buckling and growth. Based on different assumptions, “thin film” and “general” models were introduced. Delamination growth was studied using strain energy release rate method. It was found that under compression, the growth of delamination may be stable, unstable or an unstable growth followed by a stable growth. Kassapoglou [11] proposed a nonlinear analysis to model composite panel with elliptical delaminations or disbonds under compressive loadings, it is shown that there is a delamination threshold size below which the panel behavior is not affected by the presence of the delamination. Kyoung and Kim [12] considered shear deformation effect and proposed a one-dimensional analytical model to determine the delamination buckling load and growth of one-dimensional delaminated beam-plates. Results of their analysis show that the buckling load is dependent on the configuration of the delamination and shear deformation effect lower the buckling load and increase the strain energy release rate.

For composite structures containing multiple delaminations, Kutlu and Chang [13] developed an analytical finite element model along with experiments to study the response of laminated composites containing multiple through-width delaminations. It was found that the response of composites with multiple delaminations could be quite different from that with single delamination and multiple delaminations reduce compression strength more than single delamination. Lim and Parson [14] used an energy method to compute the liberalized buckling load of delaminated composites, in their study, Euler beam buckling, thin film buckling or antisymmetric S-shaped buckling modes were observed depending on the amount of delamination and geometry of delamination. Suemasu [15] investigated compressive buckling stability of composite panels with equally spaced multiple through-width delaminations analytically and experimentally. The analytical method was based on the Rayleigh-Ritz approximation technique and Timoshenko type shear effects were also included. In his paper, it is suggested that compressive buckling stress suddenly starts to decrease when multiple delaminations reach a certain length, the panel with multiple delaminations tends to kink at the delaminated portion by very low load, even when the size of delamination is not long and buckling load decreases when the multiple delaminations approach the clamped ends. Hwang and Liu [16] used a nonlinear finite element method to predict the buckling stress and correspondent buckling modes of composite with multiple delaminations. The results indicate that buckling stress and buckling mode were dependent on the length of near surface delamination length and beneath delamination length.

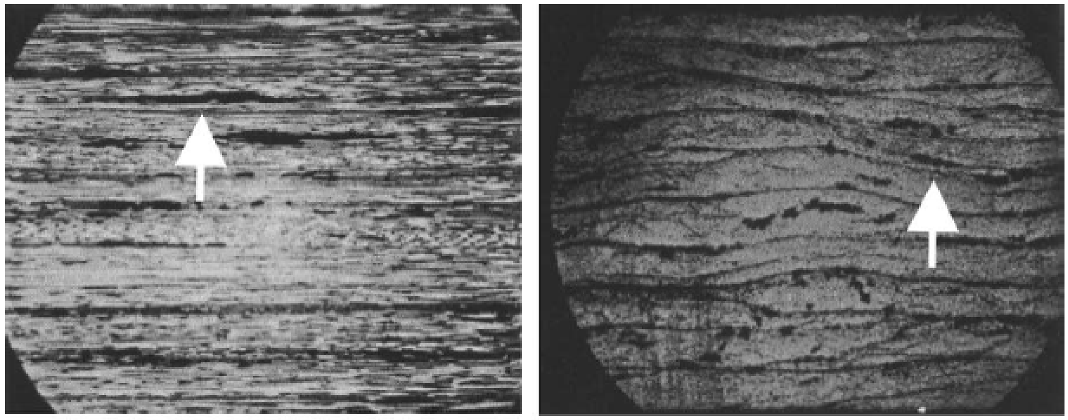
The studies described above give us clear understanding of overall delamination buckling behaviors under compression. However, as what could be expected, compressive buckling behavior is a mix-mode fracture behavior, Mode I, Mode II or even Mode III fracture would affect the compressive buckling behavior. As a result, it is necessary to study the individual fracture mode to see how they related to the compressive buckling behavior. Whitcomb [17, 18] performed 2-D parametric study of the strain energy release rate on the post-buckled through-width delamination. In his study, stress distribution and strain energy release rate were calculated for various delamination lengths, delamination depths, applied loads. It was found that calculated strain-energy release rates for Mode I and Mode II crack extension were found to be very sensitive to delamination length, delamination depth, and load level. It was also suggested that delamination growth is dominated by Mode I strain energy release rate G_I while G_{II} is much larger than G_I. He then extend the study to the 3-D plates with embedded post-buckled delamination [19, 20] and found that both Mode I and Mode II strain energy release rate varied along delamination front.

From what we discussed above, it is obvious that compressive buckling behavior is complicated and is closely related to delamination geometry. As a result, when dealing with such problems, it is necessary to highlight the prescribed delamination conditions, e.g. the position of delamination, type of delamination, as these conditions may affect the buckling behavior and neglecting these may result in an unreasonable physical model.

3. Voids in composites and their effects

The manufacturing induced defects may have beneficial or deleterious effects on the mechanical properties of composite structures. Since it is difficult and costly to manufacture defect free composite structures, it is of interest and importance to consider manufacturing induced defects and their effects on the behavior of composite structures in the structural analysis. By accepting certain amount of manufacturing defects while still meeting structural performance requirements we could reduce the production cost and reach the best use of materials.

Voids are probably the most common found manufacturing defects in the composite structures. There are two main causes of voids, one is the entrapment of the air during the impregnation of the fiber reinforcement with fiber and the other is volatile arising from the resin system itself [2]. The formation of voids is controlled by many manufacturing parameters, such as vacuum pressure, cure temperature, autoclave pressure, resin viscosity [21, 22]. Meanwhile, different composite system may result in different type of voids. A typical view of voids in the unidirectional composites is shown on Fig.4.



(a) A section parallel to the fiber direction (b) A section perpendicular to the fiber direction

Fig. 4. Voids in the unidirectional composites [4].

It has been shown that many mechanical properties such as interlaminar shear strength, transverse and longitudinal modulus, fatigue resistance would decrease in the presence of void [2]. Some experimental efforts have been devoted to investigating the void effects on the composite structures. Most of them tried to determine the relationship between void contents and mechanical properties of composite materials. In their studies, different void contents could be achieved by varying processing parameters. Bowles et al. [4] studied the 12-ply unidirectional graphite composite and found that the distribution of voids within the composites became more homogeneous as the void content increased. In those laminates with low void content, the voids appeared to be more segregated in one area of the laminate. Meanwhile, interlaminar shear strength was also found to decrease significantly with the increase of void content. In their study, a spherical and a cylindrical void model were developed to predict the interlaminar shear strength value but achieved relatively poor result with experimental data. Ghiorse [23] conducted the short beam shear and three-point flexure experiment on a series of $[0/90]_{4s}$

laminates with varying void contents and found that in the range from zero to 5 %, each 1% increase in void content corresponds to a decrease of 9.7% in interlaminar shear strength, 10.3% in flexural strength, and 5.3% in flexural modulus in carbon/epoxy composites. Wisnom et al. [6] studied the effect of discrete and distributed on the interlaminar shear strength of glass/epoxy and carbon/epoxy unidirectional composite plates and found a reduction between 8%-31% in the interlaminar shear strength depending on the void size. In this paper, they also suggested that the observed reduction in the interlaminar shear strength is a combination of the reduction of cross-section area due to distributed voidage and initiation of failure from large discrete voids. For graphite/epoxy unidirectional and fabric composite laminate, Jeong[24] also found that interlaminar shear strength decrease with the increase of void contents.

The effects of voids on the fracture toughness were also measured. Asp and Brandt [25] conducted pure Mode I, Mode II and mixed mode tests to investigate the effects of pores and voids on the interlaminar delamination toughness of a carbon/epoxy laminates. Voids were found to have a deleterious or no effects on the critical strain energy release rate at crack growth initiation. However, at propagation in pure Mode I and mixed mode load-cases the presence of voids was found to increase the critical strain energy release rate. They suggested this result could be attributed to a change in the failure mechanism. In their experiments, a significant amount of crack bridging were established at the crack tip in the void free specimens, however, in the specimen containing voids, ply splits were observed to bridge the crack which resulted in an increase in the critical strain energy release rate. Mouritz [26] studied the relation between increasing void content and Mode I fracture toughness in the glass fiber composite laminates. Mode I fracture toughness was found to fall with increasing void content and remain low and reasonable constant at void contents above ~15%. However, different from what was found in [25], the branching, which occurred at the crack tip, was not extensive enough to allow the delamination to jump between plies, and as a result, delamination was confined to the mid-plane of DCB specimen. Therefore, these composites suffered a reduction in interlaminar delamination toughness with the increase of void content because pores facilitated the initiation and growth of the delamination.

Prakash [27] conducted the fatigue experiment to investigate the void effect on the fatigue failure of Carbon Fiber Reinforced Plastics and proposed a hypothesis that in the area where defects such as voids exist, heat dissipation rate may be less than that containing sufficient amounts of fibers, thus defects may be a potential heat accumulation zone and a further rise in temperature may occur under cyclic loading, which acts as a promoter to the crack initiation process. Almeida and Neto [28] found that voids have a strong detrimental effects on the fatigue life of structures if void contents is above a critical value. Suarez et al. [29] conduct a compressive experiment to find a quantitative relationship between void content and compressive strength for carbon/epoxy laminates. It was found that with the presence of up to 4% of void content, the compressive strength decreased to 60% of ideal strength, at a rate of 10% for each 1% of voids, and beyond this void level the rate of decrease diminished and did not fall under 50%.

Some theoretical models have been proposed to explain the behavior of composites with the presence of voids. Almeida and Neto [28] proposed to use a modified Mar-Lin criterion [30] to access the void effects on the flexural strength and fatigue life of composites under bending. Jeong [24] also modified Mar-Lin criterion [30] to explain the effects of porosity on the mechanical properties of composites. Varna et al. [31] investigated the effects of void contents and geometry on the transverse mechanical properties of unidirectional GF/VE fabric laminates and found that laminates had a transverse strain to failure as high as 2% whereas low void content laminates failed a 0.3%, they also proposed a model to explain the large strain to failure of high void content composites.

Some analytical and computational models have also been developed to study the void effects. Hagstrand et al. [32] studied the influence of void content on the structural performance of unidirectional glass fiber reinforced polypropylene composite beam based on the experimental finding and a simple analytical approach based on beam theory. In this study, they found that a negative effect on the flexural modulus and strength, which decreased by about 1.5% for each 1% of voids up to a void content level of 14%. However, a clear positive effect on the beam stiffness, EI, which increased by about 2% for each 1% of voids. Beams which contain 14% porosity exhibit about 28% higher EI than beams with less than 1% porosity. A more complex computational model was proposed by Huang and Talreja [7] to access the effect of void geometry on elastic properties of unidirectional fiber reinforce composites. Their results show that the voids have much larger influence on reducing the out-of-plane properties than the in-plane ones. Chowdhury et al. [33] also conducted a computational study focused on examining the role of manufacturing-induced voids in the initiation and growth of damage at the micro-structural level in polymer matrix composites loaded in tension normal to fibers and found that the presence of voids reduces stiffness but may allow large strain to failure by promoting the craze-induced flow. As the only literature concerning the void effect on the Mode I strain energy release rate in composite laminates, Ricotta et al. [8] proposed a modified beam-on-elastic foundation theory which accounts for shear compliance and material orthotropy and carried out a FE analysis. They suggested that the Mode I strain energy release rate in DCB specimens is significantly influenced by the transverse shear properties of the laminate, meanwhile, the presence of the void increase the strain energy release rate significantly, and the shape of voids also play a crucial role. At last, it was shown that it seems that the influence on G_I is controlled by the first two voids.

Thanks to the previous studies, we are more aware of the effects of voids and willing to consider voids in their structural performance evaluation. However, it should be noted that most of studies on voids effects have tried to correlate void contents with certain mechanical properties, which is too a simplistic way to treat voids and do not give us the best explanations of mechanism behind these effects. For example, in the study conducted by Hernandez et al. [34], as shown on Fig.5, within certain void content, interlaminar shear strength and interlaminar fracture toughness increases with increasing void content for AS4/8552 composite laminates, which contradicts to most of the previous results [2, 4]. Similar trend can also be found in fatigue test [35]. This variation of effects of voids cannot be explained simply by the void content and also indicates maybe there should be other factors that need to be considered. Lambert et al. [36] made a further demonstration of such consideration. In their study on the roles of void on fatigue of wind turbine materials, they first tried to correlate overall void content with fatigue life, but no correlation could be found as shown on Fig.6. They then investigated the relationship between larger void and fatigue. As displayed on Fig.7, a correlation could be found but 95% confidence interval is not met. Finally, they studied the role of largest void within the damage plies and correlated them with fatigue life. From Fig.8, it is clearly that correlation is found, and 95% confidence interval is met. These results have well demonstrated the fact that the method using void content alone to explain the effect of void on mechanical properties of composites is too simplistic. At the same time, void shape, size, distributed within critical volume have to be considered, and these have been proven by some recent analytical results [7, 8].

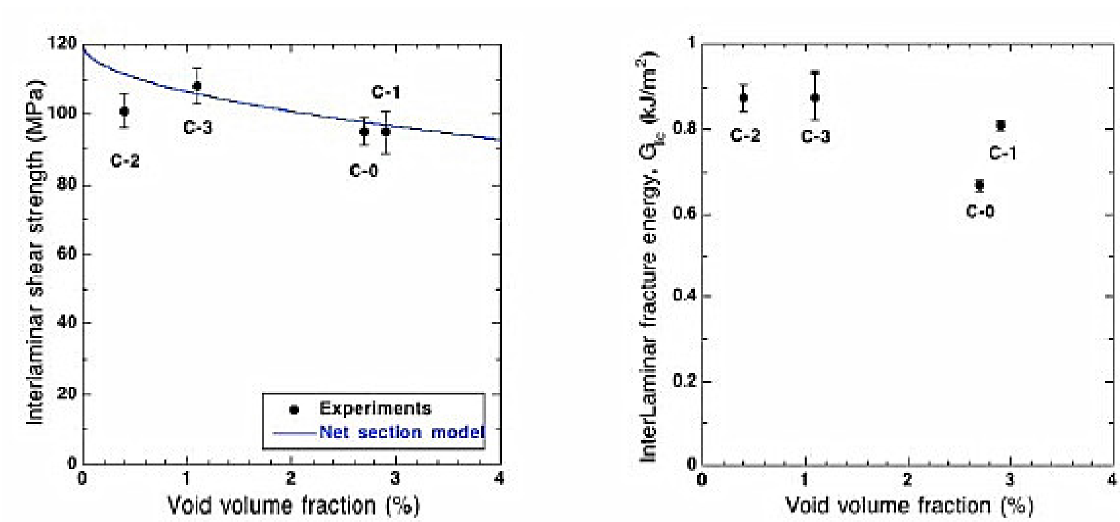


Fig. 5. Variation of void effects on ILSS and Interlaminar fracture toughness [34].

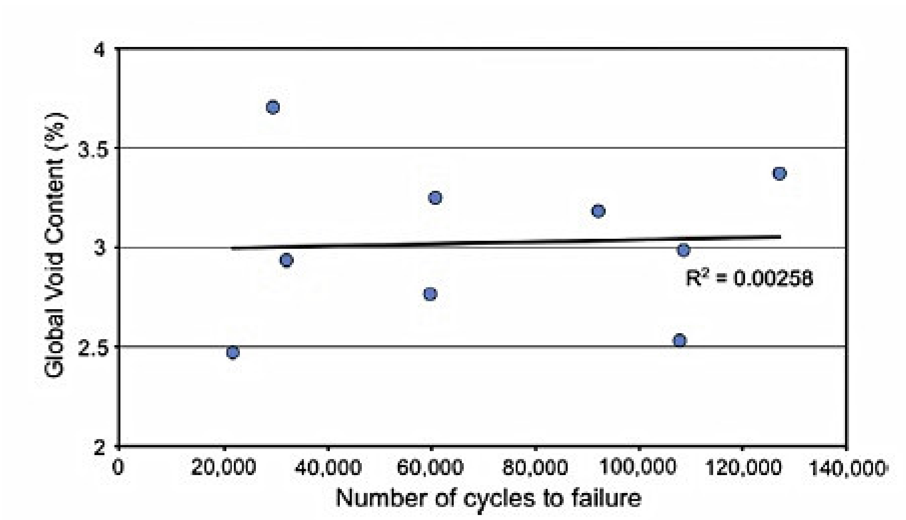


Fig. 6. Comparison between overall void content with specimen fatigue life [36].

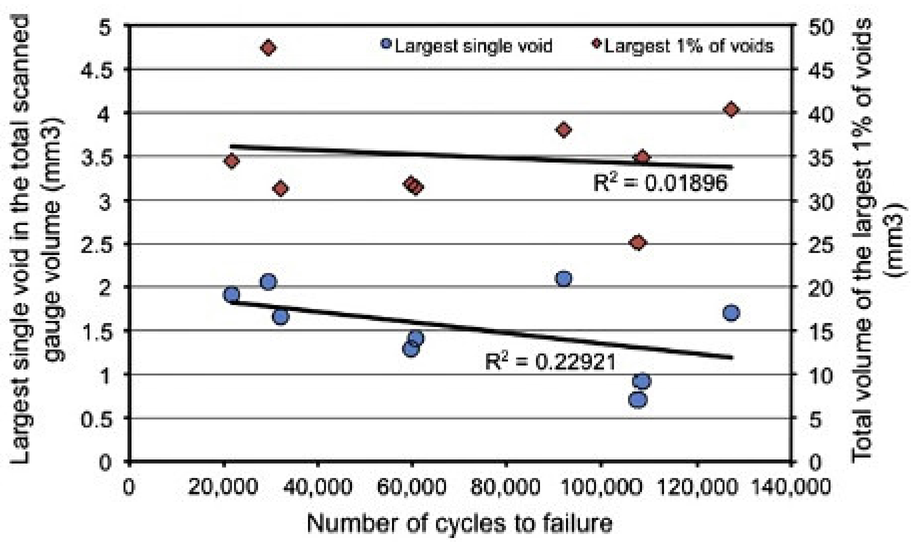


Fig. 7. Comparison between the largest void in the volume (primary y-axis), the total volume of the largest 1% of voids (secondary y-axis) and the specimen fatigue life (x-axis) [36].

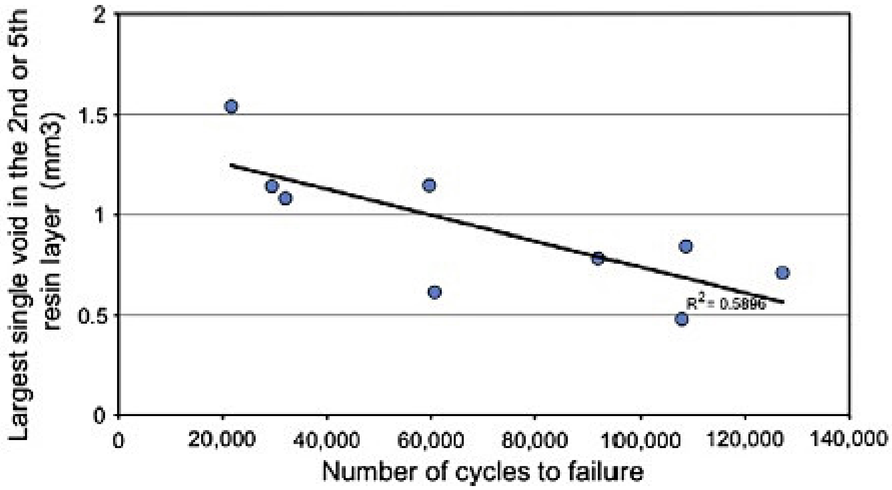


Fig. 8. Comparison between largest void within damage plies and specimen fatigue life [36].

Based on what we discussed above, it is clearly that the presence of void would affect many mechanical properties especially interlaminar related properties such as interlaminar shear strength and interlaminar fracture toughness. However, only a few studies have focused on the compressive strength and even fewer studies were conducted to investigate how the presence of voids affects the behavior of composites with delamination under compression. As to many composite structures, it would inevitably sustain compressive loads during service. Take composite wind turbine blade as an example, Fig.9 shows downwind skin and main spar section of a wind turbine blade which sustains compressive loading under flap-wise bending test, buckling driven delamination and surface debonding were found. Since these parts mainly sustain compression during the service, we may ask how do these damages affect the overall performance of wind turbine blade structure and what if delamination and debonding occurs within the high voids contents areas, how do those voids affect the structural performance? These questions are yet to known. Since all the blades are designed to have a certain amount of service year, it is important to understand how they perform if delamination or debonding occurs and whether the void would facilitate the damage evolution or hinder it? As a result, it is vital to study the effects of voids on delaminated composites under compression.

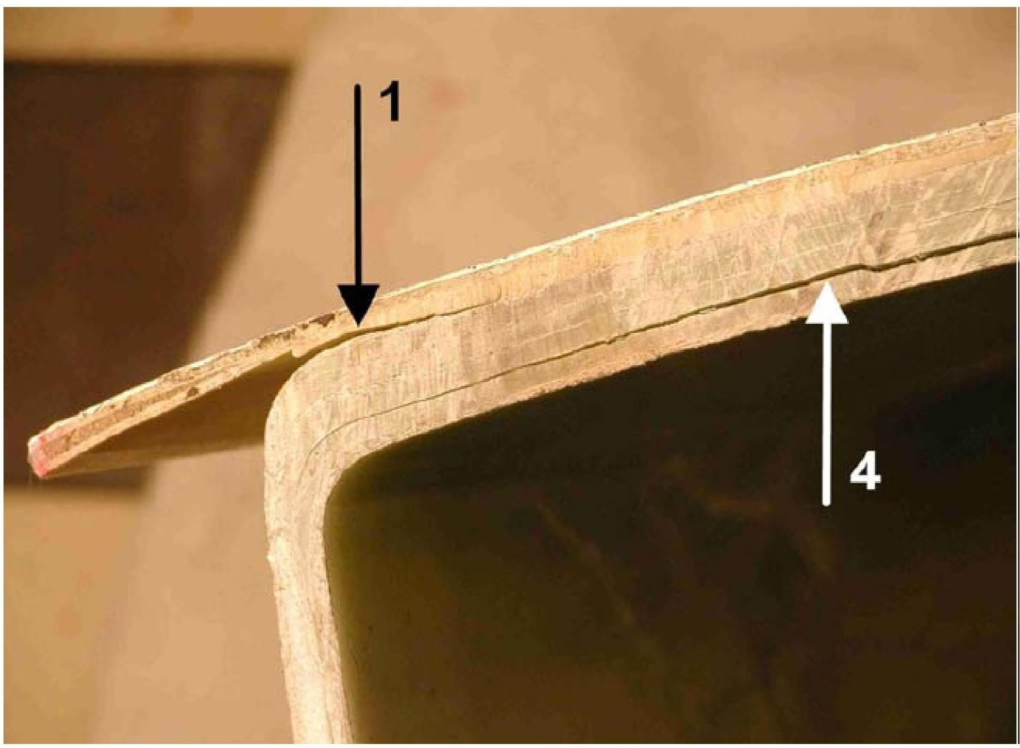


Fig. 9. Illustration of damage in downwind skin and main spar of composite wind turbine blade under flap-wise bending test. Damage type1: main spar flange/adhesive layer debonding, type 4: delamination driven by a buckling load [37].

B. Problem statement and approach

The damage mode we study here is the out-of-plane buckling of delaminated composites under compression. The problem can be simplified as a composite plate with single through-width surface delamination, when it is loaded compressively, local buckling is assumed to occur. The model could be further simplified to a 2-D problem as illustrated on Fig.10. As what we discussed above, to account for the effect of voids, void shape, void size and void distribution within critical volume should be considered. Thus in this study, the void is placed right ahead of delamination front, which is the most critical location and different sizes of void were chosen in order to study the effect of void size on the obtained results.

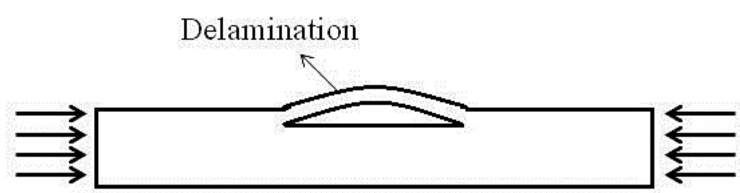


Fig. 10. 2-D illustration of local buckling of laminate with through-width delamination.

Strain Energy Release Rate (SERR) is studied as the driving force for the delamination growth. As can be expected, when loaded compressively, delamination front would experience a mixed-mode fracture, e.g. Mode I and Mode II fracture in the current study. In order to account for the effects of void on each SERR component, Virtual Crack Closure Technique (VCCT) is adopted to calculate the SERR.

CHAPTER II

NUMERICAL STUDY OF DELAMINATION BUCKLING WITHOUT VOID

In this chapter, delamination growth of composites without void is investigated in order to make a comparison with the void case presented in the following chapter. Composite laminate with a single through-width surface delamination was considered, and a 2D Finite Element (FE) model was created. A geometrically non-linear FE analysis was performed to study the post-buckling behavior, and SERR was calculated by applying VCCT.

A. Composite laminate specimen description

In this study, the problem is simplified to a unidirectional composite plate with a single pre-existing through-width surface delamination, as shown on Fig.11. Material properties from [18] are adopted here, as displayed in Table.1. The plate is clamped at both end and loaded compressively. The gauge length of composite specimen "2L" is chosen as 100mm, and thickness "H" is 2mm. the length of delamination part "2a" is 30mm with a ratio of delamination length to gauge length equals to 0.3. The depth of delamination along thickness "t" is 0.25mm; thus the ratio of delamination depth to thickness is 0.125. For this configuration of delamination, local buckling is expected to occur when loaded compressively, which has been proven experimentally [38]. Because of the symmetric, only half of the plate was modeled, and symmetric boundary conditions were imposed the half plane. At y=H-h, displacement along the y direction was constrained in order to induce local buckling behavior. At L=50, displacement boundary condition was used to simulate the loading.

Table 1 Elastic properties of composite lamina[18]

E_{11} (MPa)	E_{22}(MPa)	G_{12}(MPa)	V_{12}(MPa)
149	14.9	5.9	0.21

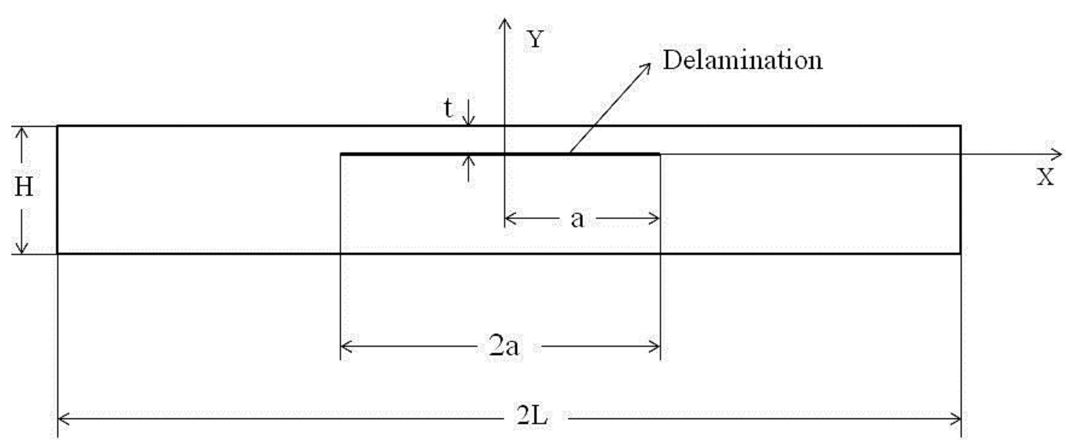


Fig. 11. Illustration of the model without void.

Strain energy release rate (SERR) was studied as the driving force for delamination growth. The FE analysis of SERR was made by applying the VCCT. The finite element method has been used for solving linear elastic fracture mechanics problem. Since it was first proposed [39], VCCT has been a useful technique to calculate stress intensity factors or strain energy release rate. Raju [40] then expanded it for higher order and singular finite elements. To get more details about VCCT, Krueger [41] made a good review about it. VCCT is based on the assumption that the energy required to extend crack to a certain length if identical to the energy required to close the crack for the same length. As can be expected, mixed mode delamination would happen in the current study, thus by adopting VCCT we are able to calculate strain energy release rate of different fracture mode separately in only one step analysis.

As recommended when using VCCT, the region near delamination front was modeled by symmetrical regular shape elements of uniform size, as show on Fig.12. The element size "e" was equal to 0.0125mm. Tay et al[42] has proven that mesh refinement would not alter obtained SERR too much if near tip mesh is symmetric and contains square element, as a result, current mesh is sufficient to compute the SERR.

Equations for computing the Mode I and Mode II strain energy release rate are adopted from [40], for eight node non-singular elements, the SERR s are obtained by eq.(1) and (2),

$$G_{I=}-\frac{1}{2e}\left[F_{yi}\left(v_m - v_{m'}\right) + F_{yj}\left(v_l - v_{l'}\right)\right] \quad (1)$$

$$G_{II=}-\frac{1}{2e}\left[F_{xi}\left(u_m - u_{m'}\right) + F_{xj}\left(u_l - u_{l'}\right)\right] \quad (2)$$

Where

F_{yi} and F_{yj} is the y direction force at node i and j respectively as shown on Fig.13 corresponding to the opening action. F_{xi} and F_{xj} are the x direction force at node i and j corresponding to the sliding action. "u" and "v" represent the displacement along X and Z direction, respectively, subscripts represent the nodes we are studying.

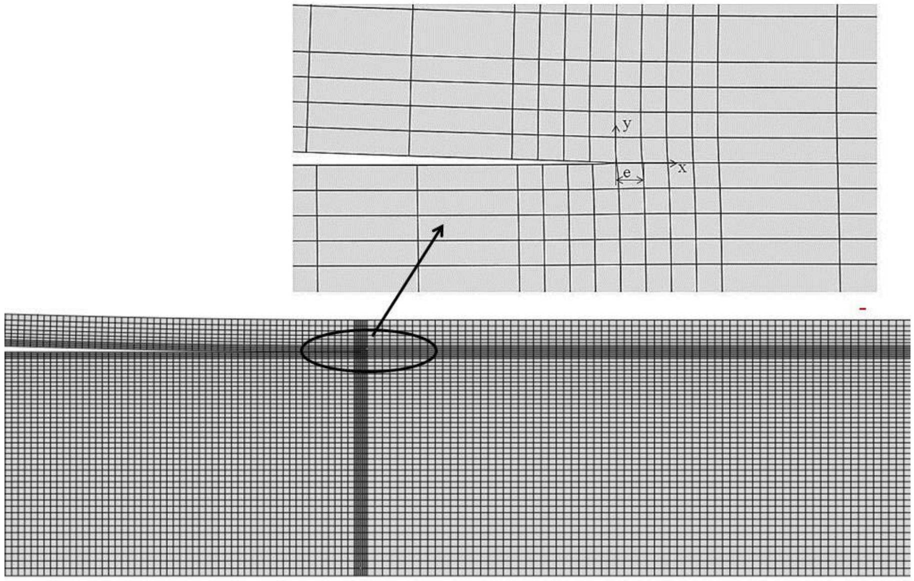


Fig. 12. Detail of finite element mesh.

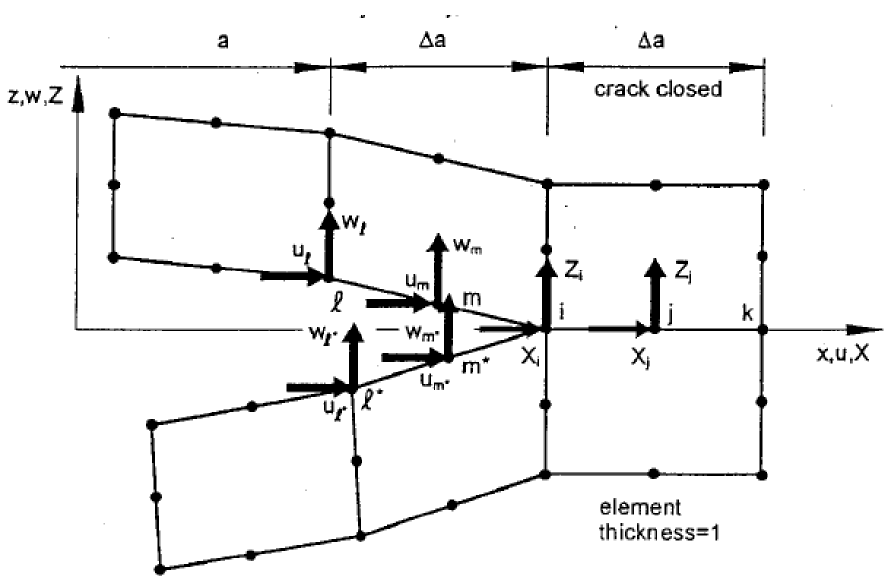
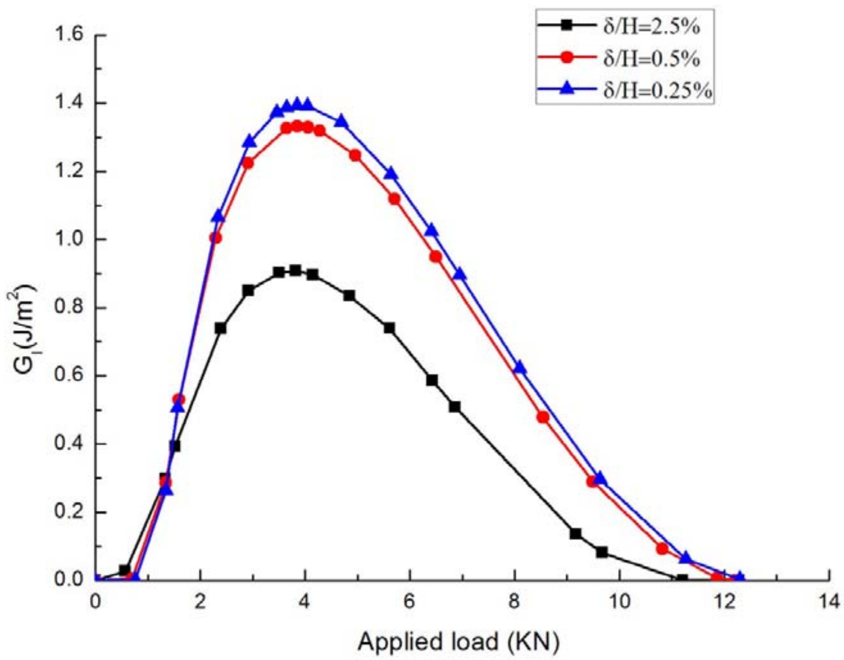


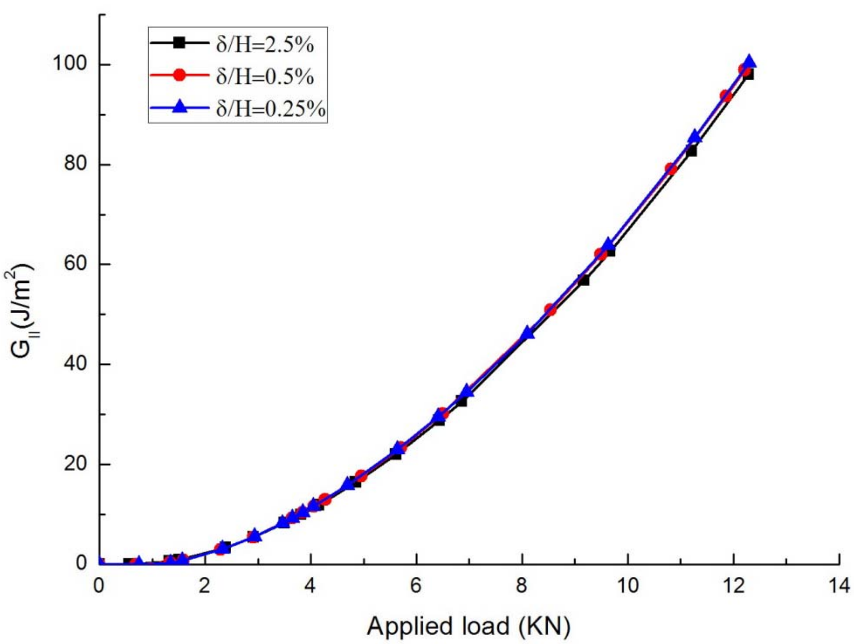
Fig. 13. Illustration of VCCT method [40].

A geometrically non-linear FE analysis was performed using software ABAQUS. Eight node plane strain quadrilateral elements were adopted, as recommended in [17], reduced integration scheme was also used in order to improve the performance of two-dimension elements. The typical mesh used is shown on Fig.12. In the non-linear post-buckling analysis, a small transverse displacement "δ" is usually introduced in order to initiate the buckling behavior. Here, three different values of initial transverse displacement were chosen in order to determine its effect of on the obtained SERR (δ/H=0.25%, 0.5% and 2.5%). Fig.14 (a) shows the obtained Mode I SERR value G_I with respect to the applied load, it is shown that the difference of initial transverse displacement only affects the maximum value of G_I, it does not alter the trend of G_I, and the applied load levels when G_I reaches its maximum value are almost the same. From Fig.14 (b), it is clearly that the difference of initial transverse displacement has little effect on the Mode II SERR value and if we compare G_I and G_{II} value, G_{II} is much larger than the G_I, as a result, the choice of initial transverse displacement would have little effect on the final result. Hence, initial transverse displacement δ/H=0.5% was selected in the current study.

Contact constraint was not imposed in the model, and this would result in potential crack face overlap in the FE analysis. However, as mentioned in [18], when the delamination front closes, the total SERR from the non-contact analysis do not change significantly compared with the result obtained from contact analysis and its value can be used as an approximation of G_{II} value. Since in the current study, we are only interested in the behavior of delamination part before contact, as a result, in order to simplify the FE analysis, crack face overlap was allowed.



(a)



(b)

Fig. 14. Effect of initial transverse displacement on obtained SERR (a) G_I value (b) G_{II} value.

B. FE model validation

The validation of the FE model was done by compared the obtained SERR result with the "thick column" model proposed by Chai et al. [10]. There were three different scenarios being discussed in their paper; one was the "thin film" model which assumed a surface delamination with an infinite thickness of laminate, a general model containing both local and global buckling of the laminate, and the "thick column" model, which has a finite thickness of laminate and the thickness is large compared to the delamination depth. The "thick column" model matches the case we are studying. As a result, SERR obtained by "thick column" model was adopted to compare with the FE results. To further validate the current FE model, the result was compared with the result obtained by another FE evaluation using J integral with the same mesh. It should be noted that for both "thick column" model and J integral method, they could not separate the Mode I and Mode II value of SERR, and thus results obtained corresponds to the total SERR. As a result, in order to make a comparison, the values of G_I and G_{II} obtained from VCCT were added together. As shown on Fig.15 and Fig.16, the FE calculation by VCCT agrees well with both analytical model and FE calculation by J integral (6.6% maximum difference).

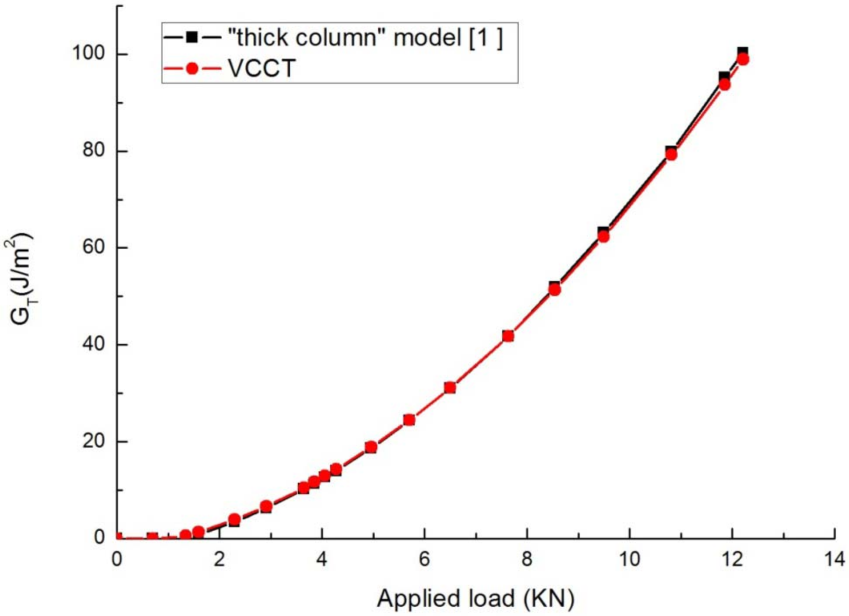


Fig. 15. Comparison of SERR results between VCCT and referenced analytical model.

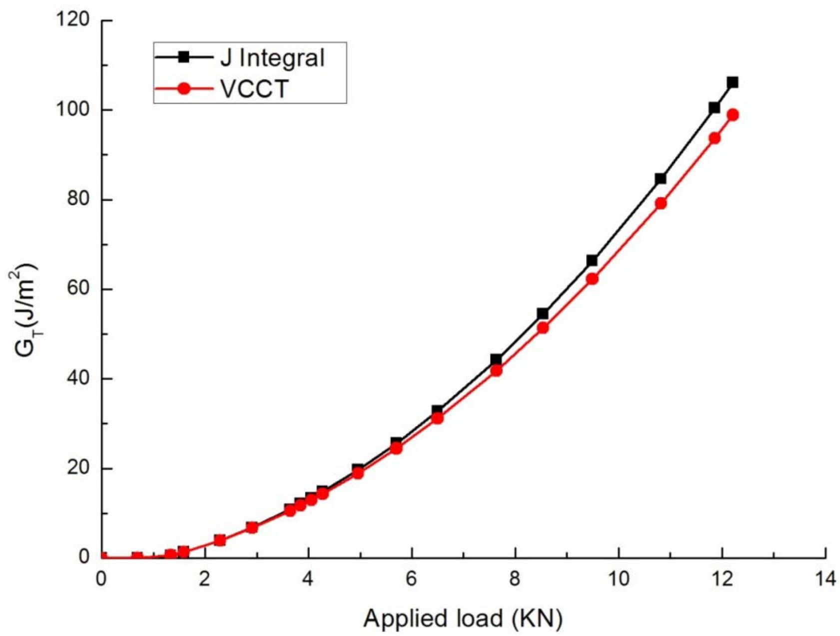


Fig. 16. Comparison of FE evaluation results between VCCT method and J integral method.

C. General post-buckling behavior of delaminated part

General deformed shape of FE model is shown on Fig.17 and profile of delaminated parts under different loading level is displayed on Fig.18. From Fig.17, it is shown that when out-of-plane buckling occurs, delaminated part can be divided into two parts: one is with convex shape while the other part closer to the delamination front displays a concave shape. This characteristic can be seen more clearly from the delamination profile displayed on Fig.18, and how this feature would affect the buckling behavior would be discussed later. It should be noted that on Fig.18, 0 and 15 in the abscissa corresponds to the mid-plane of delaminated part and delamination front, respectively. Thus from Fig.18, we could see that the maximum transverse displacement increases with the increase of applied load. Fig.19 and Fig.20 show the calculated results of G_I and G_{II} with respect to the applied load, respectively. The mode I SERR G_I increases to a peak value when the applied load reaches a certain level and then decreases with increasing load. However, G_{II} increases with increasing load monotonically. Meanwhile, it is important to note that G_{II} is much larger than the $G_{I.}$ As a result, if we compare total SERR G_T with $G_{II,}$ as illustrated on Fig.21, we can see that G_T almost follows the same trend as $G_{II,}$ and the slight difference between those two at the beginning is due to the G_I contribution.

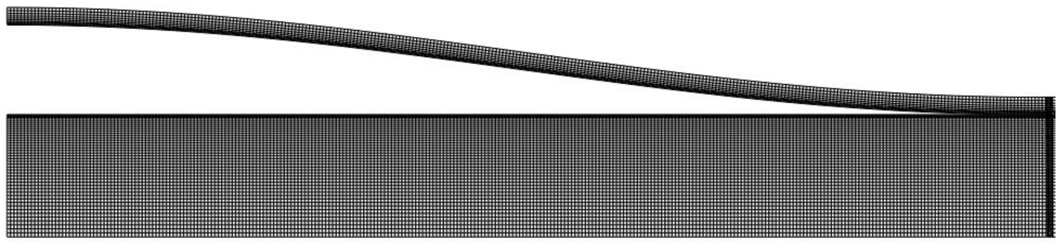


Fig. 17. General deformed shape of FE model without void.

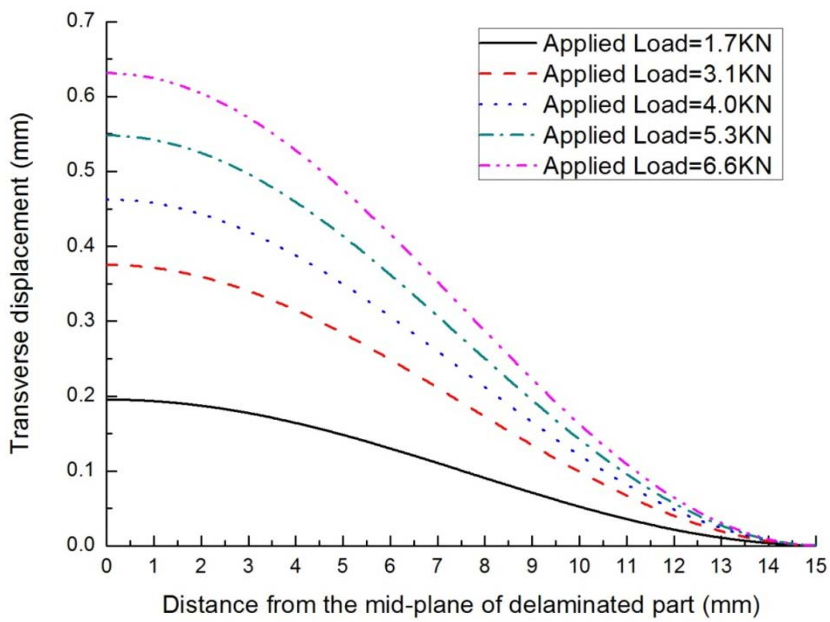


Fig. 18. Delamination profile of delaminated part under different loading level.

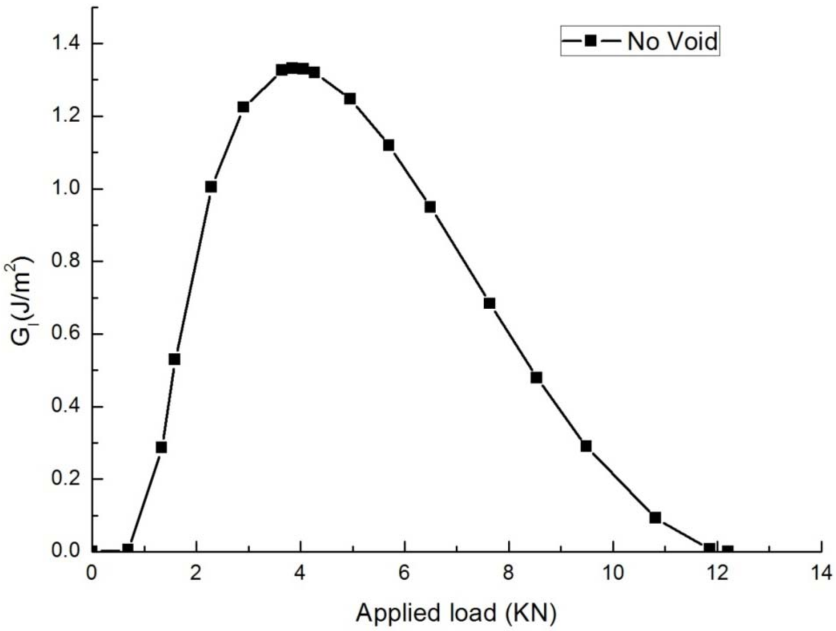


Fig. 19. Mode I SERR vs. applied load.

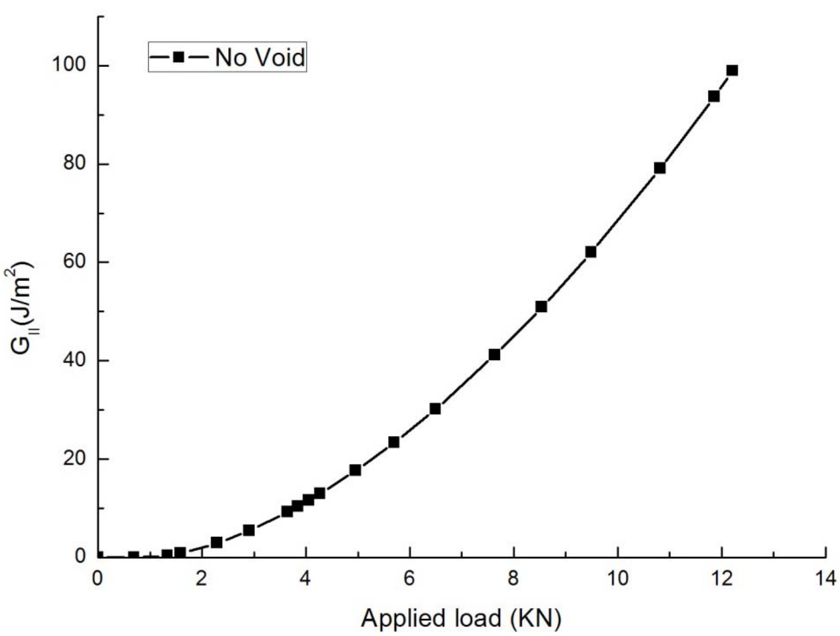


Fig. 20. Mode II SERR vs. applied load.

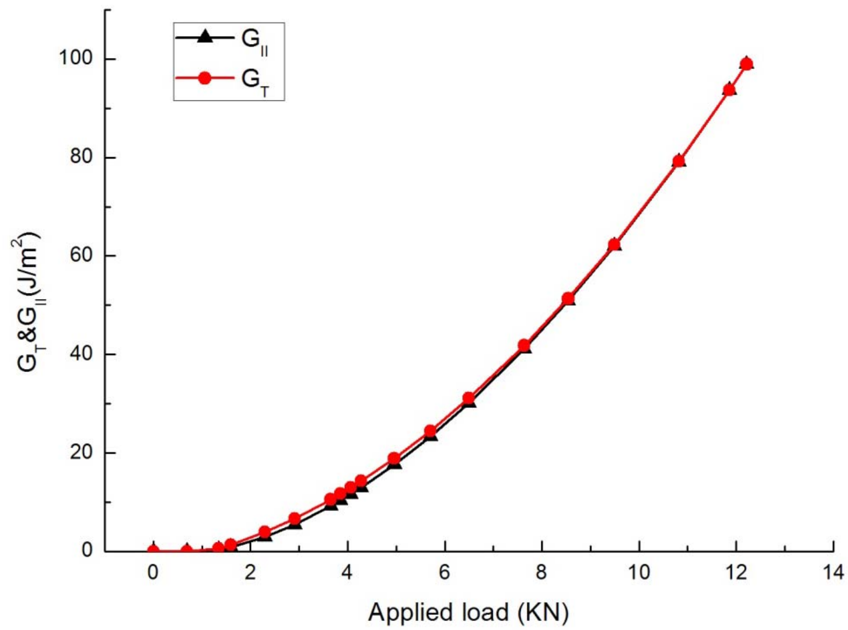


Fig. 21. Comparison between G_T and G_{II}.

As what has been shown on Fig.19, G_I does not increase monotonically with increasing load. Since G_I value corresponds to the opening behavior of delaminated part, it is interesting to study the opening action of post-buckling behavior of delaminated part. From Fig.18 we've already known that maximum transverse displacement increases with the increase of applied load, so here we study the behavior of the region near delamination front, which corresponds to the concave delamination profile part. Fig.22 shows the delamination profile of the region near delamination front under different load levels. From Fig.19, we can see that when the applied load is around 4KN, G_I value reaches its peak value, so if we look at Fig.22, we can find that before 4KN, in other words, before G_I reaches its maximum value, the transverse displacement of the region near the delamination front is increasing with increasing load, which means delamination front is still opening. However, when the applied load is higher than the 4KN or after G_I reaches its maximum value, the transverse displacement of the region between delamination front and a certain distance from it starts to drop, which means delamination front begins to close. As applied load increases, the region where transverse displacement decreases expands, which is marked by circle on Fig.23, and further increase of the applied load would lead to the closure of delamination front, which corresponds to G_I equals to zero. These results indicate that the obtained G_I SERR could be used to correlate the opening behavior of delamination front.

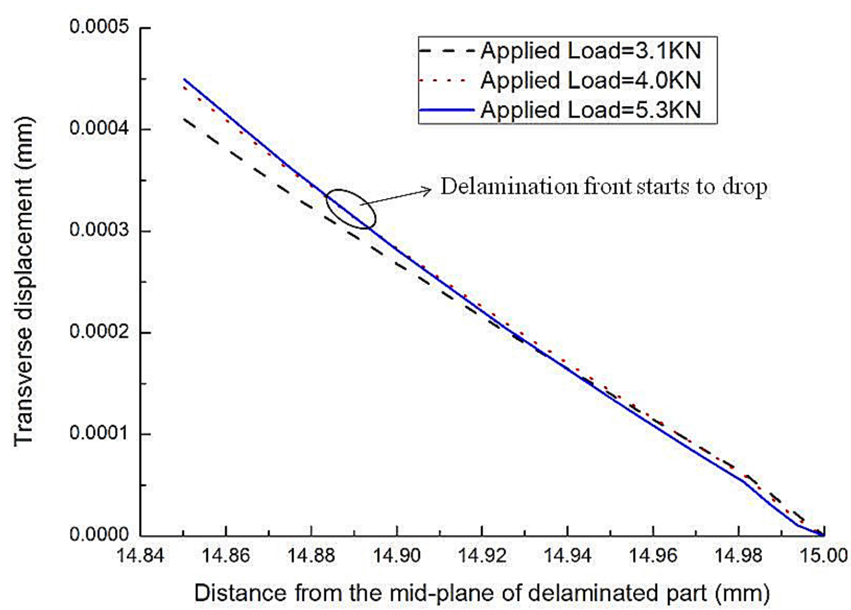


Fig. 22. Delamination profile of the region near delamination front under different loading level.

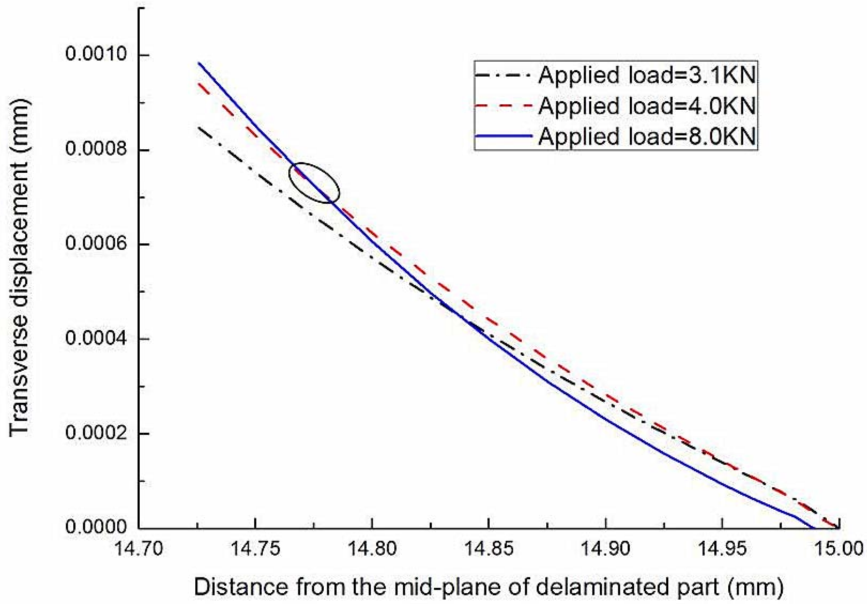


Fig. 23. Delamination profile of the region near delaminated front under further loading.

D. Summary

Numerical study was performed to investigate the delamination growth under compression. It is found that when the delaminated plate is loaded compressively, out-of –plane buckling would occur, and the delaminated part would be divided into two parts, which exhibit different post-buckling behaviors. Based on the study, following conclusions can be drawn:

(1) Mixed-mode delamination is found when the delaminated laminate is loaded compressively.

(2) G_I value increases to a peak value and then decreases with the increase of applied load.

(3) G_{II} value increases monotonically with increasing load.

(4) G_{II} component is much larger than the G_I component.

(5) Under compressive loading, Delamination front would open first and then starts to close when the applied load reaches a certain level. Further increase of apply load would lead to the closure of delamination front. This behavior corresponds to the G_I trend.

CHAPTER III

NUMERICAL STUDY OF DELAMINATION BUCKLING WITH VOID

Delamination growth of composites in the presence of void is studied at this chapter. In the 2D FE model, delamination geometry is the same as described in the previous chapter. A Geometrically non-linear FE analysis was performed, and void effect on post-buckling behavior was investigated through FE model.

A. Characterization of void

Huang and Talreja [7] made a review of typical void characteristics in composite laminates, and the average sizes of voids in the unidirectional laminates manufactured by autoclave process were summarized, as shown on Table.2. As sketched on Fig.24, voids are mostly found to be elongated cylindrical, cigar shape running along the fiber direction, in the cross sections the voids appear in flat elliptical shapes with short axis in the laminate thickness direction. Most of the voids are located between plies. Recent finding by the author's colleagues and the author gives a clear illustration of void view perpendicular to the fibers and the cross section view of the voids parallel to the fibers, which is shown on Fig.25 and Fig26.

Table 2 Geometric characteristics of voids in composite laminates [7]

	Length	Width	Height
Range	0.1 – several mm	10 μm to 1 mm	5 – 100 μm
Average value range	0.3 – 1 mm	30 – 100 μm	8 – 20 μm

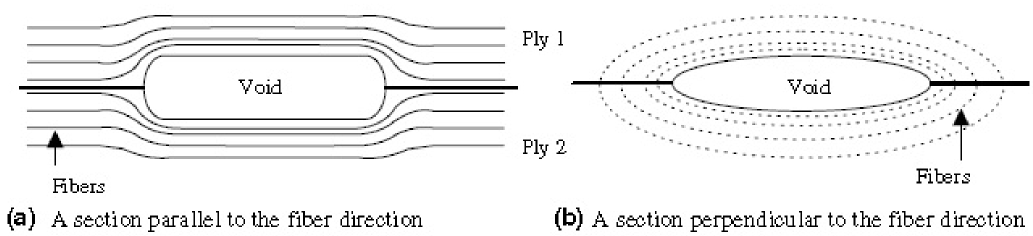


Fig. 24. Schematic illustration of voids in unidirectional composite laminates [7].

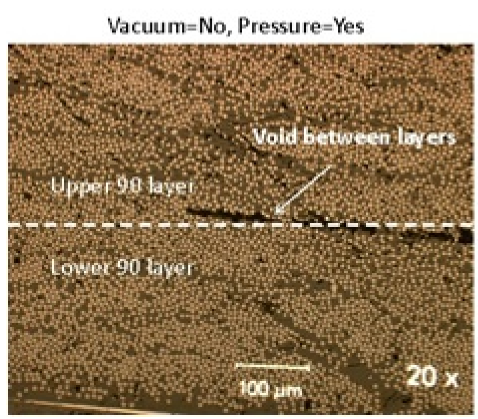


Fig. 25. A view perpendiculer to the fiber direction of voids situated between plies. Courtesy of Yongxin Huang

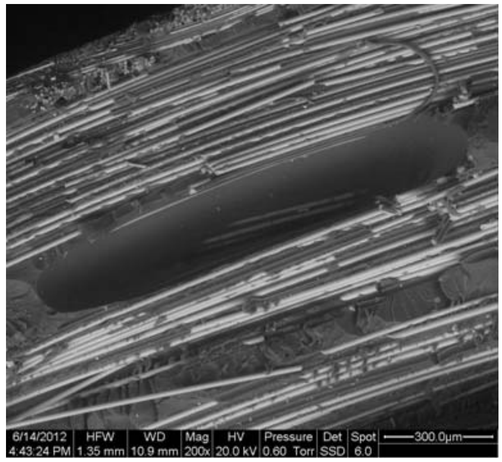


Fig. 26. A view paralell to the fiber directoin of voids in 90 layer of glass fiber tube.

B. Modeling the void

Following the similar procedure described in the previous chapter, a FE analysis was performed to study the post-buckling behavior of laminates with the presence of void.

So far, most of the studies tend to use voids content to investigate the effect of voids on the mechanical properties. However, as suggested by many researchers [3, 35, 36, 43], this approach seems to be too simplistic, many factors such as void size, shape and distribution should be considered. Some research has been conducted in order to study the distribution of voids within the laminates [35], and the result shows that the distribution of voids is non-uniform. This is not a surprising result since the nucleation of voids depends on some random events during the manufacturing process, the only information we could get is voids locate within the ply interface. Lambert et.al [36] made a further study and found that void size and void location within specific volume are two of most critical parameters. As a result, in this study, void was placed ahead of delamination front, which represents the most critical location, meanwhile, the aspect ratio (ratio between the length and the height) of the void and its distance from the delamination front were varied to order to address the importance of void size and its location on investigating the effect of voids.

The schematic illustration of the model is shown on Fig.27. Except for the dimensions related to void, the other dimensions of the model are the same as the model described in the previous chapter. Void is placed ahead of delamination front and distance between void and the delamination front is represented by “d”. The void is interpreted as a region where material is taken out. For simplicity, the cross section of cigar shape void parallel to the fiber direction is modeled as rectangular cross-section with semi-circle cap on both ends, as illustrated on Fig.27. “L_v” and “h_v” represent the length and height of the void. The plate is assumed to be clamped at both end and loaded compressively.

A geometrically non-linear FE analysis was performed. FE mesh for the delamination front and the void is shown on Fig.28. Eight node plane strain quadrilateral elements were adopted near the delamination front, reduced integration scheme was also used in order to improve the performance of two-dimension elements. As recommended when using VCCT, near delamination front mesh was symmetric. Boundary conditions for the FE model are the same as the previous case. Due to the symmetry, only half of the plate was modeled and symmetric boundary conditions were imposed the half plane.

At y=H-h, displacement along the y direction was constrained to induced local buckling behavior. At L=50mm, displacement boundary condition was used to simulate the loading. Initial transverse displacement was the same as one in previous model, no contact constrain was imposed.

It should be noted that until now, there is not any analytical model existing concerning about the effects of voids on delamination growth under compression, neither is there any experimental findings. As a result, it is hard to compare current results with some existing results. However, lack of understanding of the effects of voids on this particular field would also highlight the importance of this study. Parametric study would serve as the first step to investigate, once we've got the information about the effects of voids through parametric method, we could take a step further to study the problem analytically and then gain a solid understanding of the effects of void on delamination growth under compression.

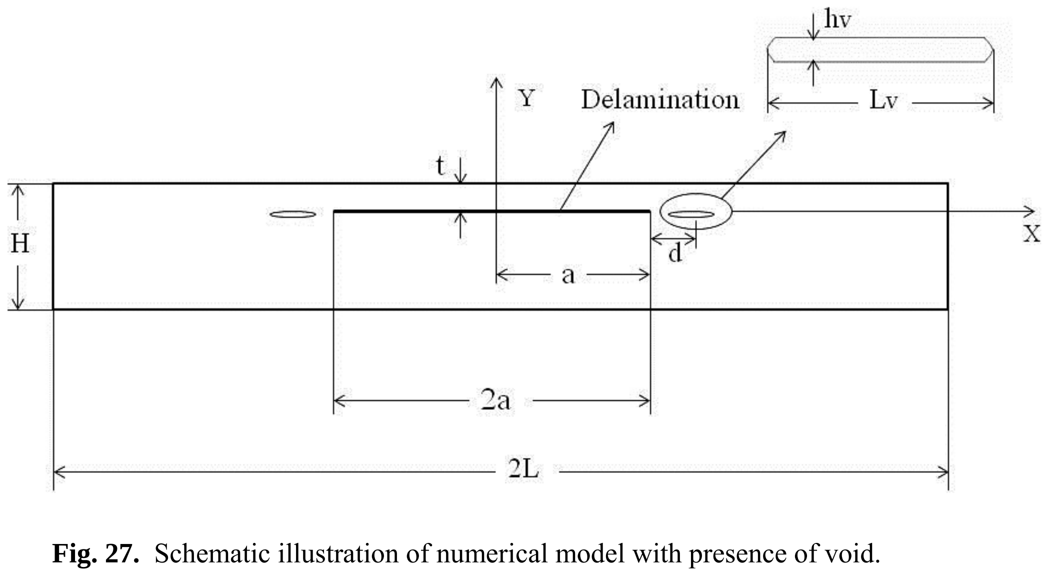


Fig. 27. Schematic illustration of numerical model with presence of void.

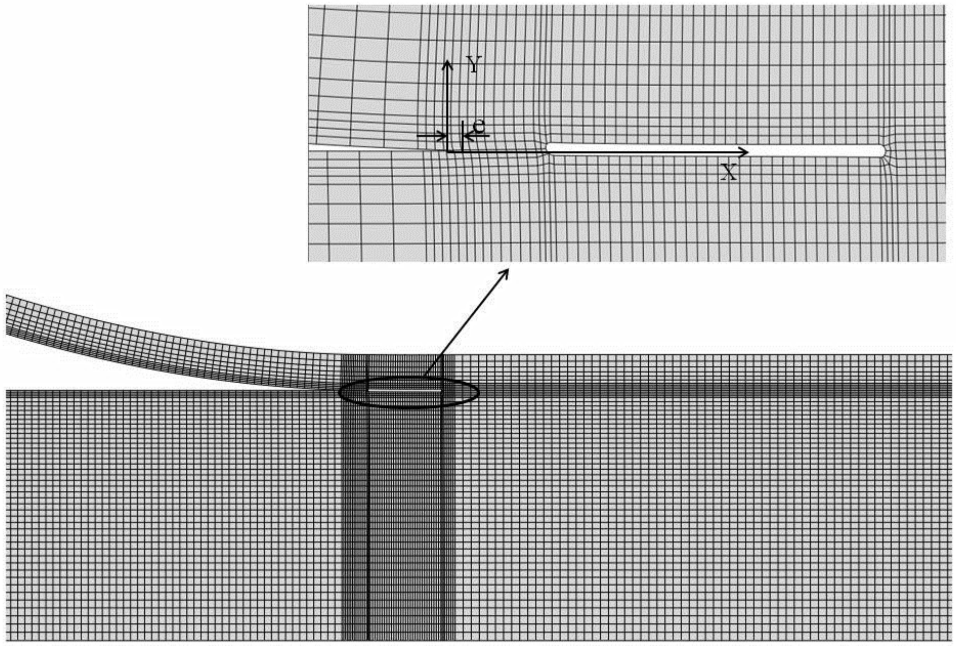


Fig. 28. Finite element mesh of the model with void.

C. Effect of void on the delamination growth under compression

1. Effect of void on transverse buckling displacement of delaminated part

The effect of single void with “L_v”=520μm and “h_v”=30μm was investigated through FE analysis. These dimensions of void were chosen based on the following reasons: (1) they could represent the common voids found in the unidirectional composites. As shown on Table.2, both dimensions are within the range of found geometric characteristics of voids (2) as a starting point, the effects of void should be apparent enough to be observed. Experimental results [28, 35] have proven the effects of void are hardly found if voids are below certain critical sizes. As a result, the void selected in the current study could be considered as large void but still well within the average voids that could be found, which could be considered as a good representative of void to study.

General deformed shape of FE model is shown on Fig.29. Similar to that of no void case, delamination contains two parts: one is convex shape part the other is concave shape part. To study the effect of void on the post-buckling behavior of laminate, the delamination profile of delaminated part in the presence of void was compared with that of delaminated part without void, 0 and 15 in the abscissa of Fig.30 corresponds to the mid-plane of delaminated part and delamination front, respectively. As shown on Fig.30 and Fig.31, when the applied loads are the same, the transverse displacements of delaminated part are almost the same for both cases, which shows that the buckling displacement is barely affected by the presence of void.

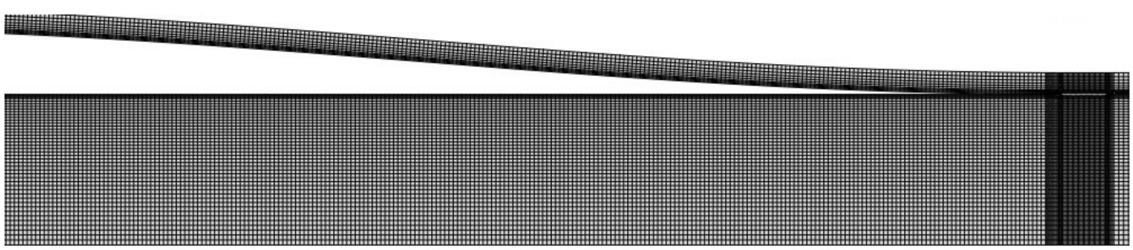


Fig. 29. General deformed shape of FE model with void.

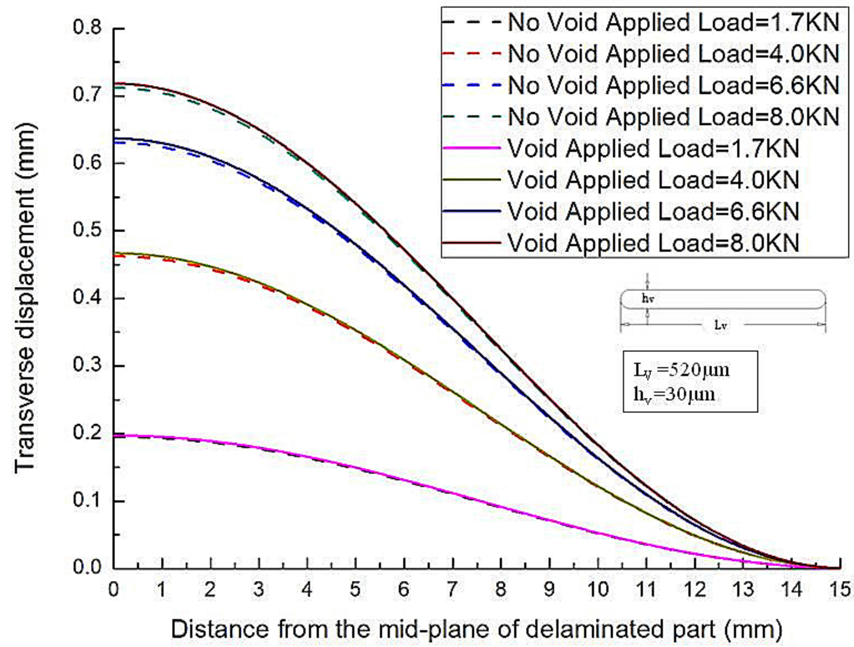


Fig. 30. Effect of void on transverse buckling displacement of delaminated part.

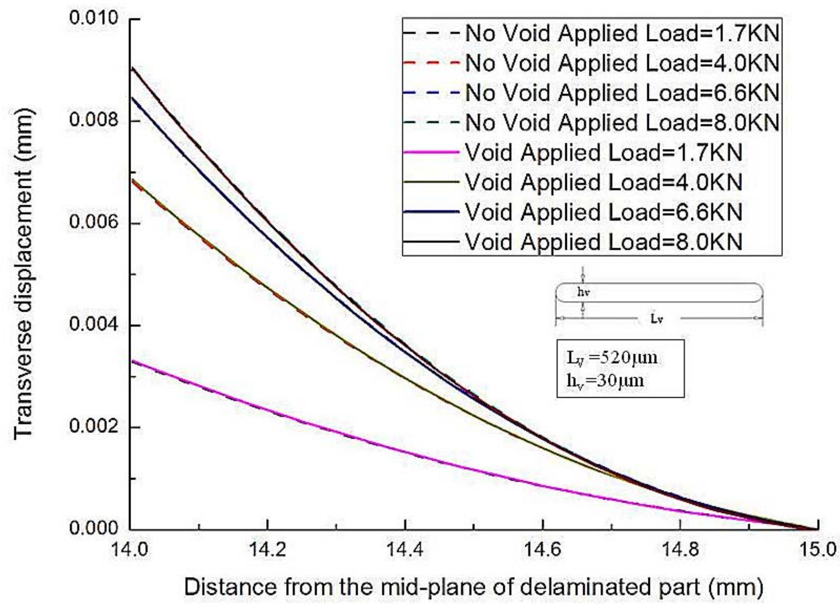


Fig. 31. Effect of void on transverse buckling displacement of the region near delaminated front.

2. Effect of void on the Strain Energy Release Rate

VCCT was adopted to calculate the Mode I SERR G_I and Mode II SERR G_{II} in the presence void. The results were compared with the results obtained from previous no void case to illustrate the effect of void on the SERR.

As shown on Fig.32, the influence of void on G_I is barely seen before G_I reaches its maximum value. Meanwhile, maximum values of G_I are almost the same for each case. After G_I reaches its peak value, the influence of void has become apparent with further increasing the applied load and the presence of void increases G_I at this moment. As what we've already discussed in the previous chapter, delamination front is opening before G_I reaches its maximum value and then is closing along with decreasing G_I. So now let us first focus on the state when the delamination front is opening. In the study performed by Ricotta et al. [8], the presence of void was found to increase the Mode I SERR under DCB test, however, no increase in Mode I SERR is found in the current study. This could be explained by two reasons: (1) the dimension in height or transverse direction of our void is much smaller than that in their study. As can be shown on Fig.33, when the void dimension in the transverse direction reduces, the effect of void on G_I becomes less apparent. Since in this study, the height of void is 0.03mm, which is much smaller than the smallest dimension 0.1mm in their study, it can be expected that the presence of void has little effect on G_I when the delamination is opening. (2) in our study, a through-width surface delamination is assumed while in their study delamination occurs at the mid of the thickness, it has been shown that G_I value would increase with increasing delamination depth [17], and thus we could imagine that as G_I increase, the effect of void would be more apparent even for a very small percentage of increase. As a result, the influence of void on G_I when the delamination front is increasing is negligible in our study. No good explanation could be provided for why the influence of void on G_I becomes more apparent when the delamination front is closing. However, it should be noted that this influence pattern has little interest from engineering point of view as G_I already passed its maximum value.

We've already known that G_I is closely related to the transverse displacement of delaminated part. However, as what has shown on Fig.30 and Fig.31, the presence of void does not change the transverse displacement of delaminated part. As a result, we cannot explain the effect of void on G_I through transverse displacement point of view. The explanation for this influence pattern would be discussed later.

The effect of void on G_{II} is shown on Fig.34. It is obvious that G_{II} is much larger than G_I, and the presence the void increases G_{II}. This result basically indicates that compared with no void case, the delamination front with the presence of void requires lower applied load in order to grow. This result is quite predictable and agrees with the experimental fact that the presence of void between layers should be detrimental to the interlaminar properties, which has been discussed in the introduction chapter. Total SERR G_T in the presence of void is calculated by adding G_I and G_{II} together. As shown on Fig.35. G_T increases with the presence the void and again, this is because it is a G_{II} dominated mixed mode delamination here. As a result, G_T is mainly due to the G_{II} contribution.

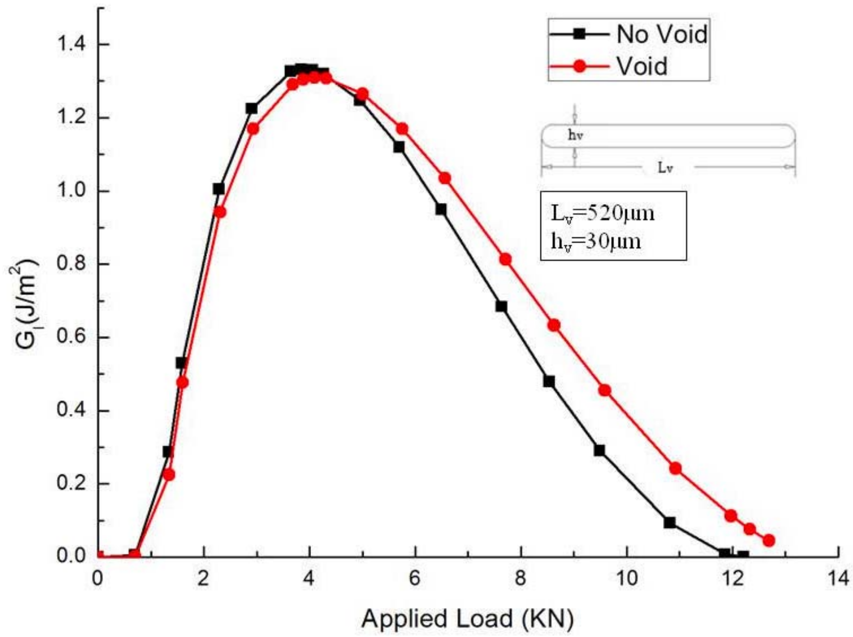


Fig. 32. Effect of void on Mode I SERR.

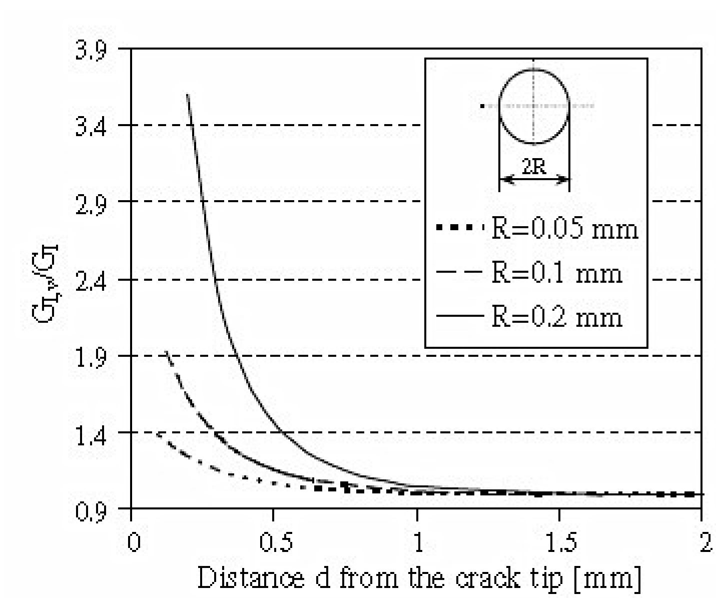


Fig. 33. Influence of void on G_I under DCB test [8].

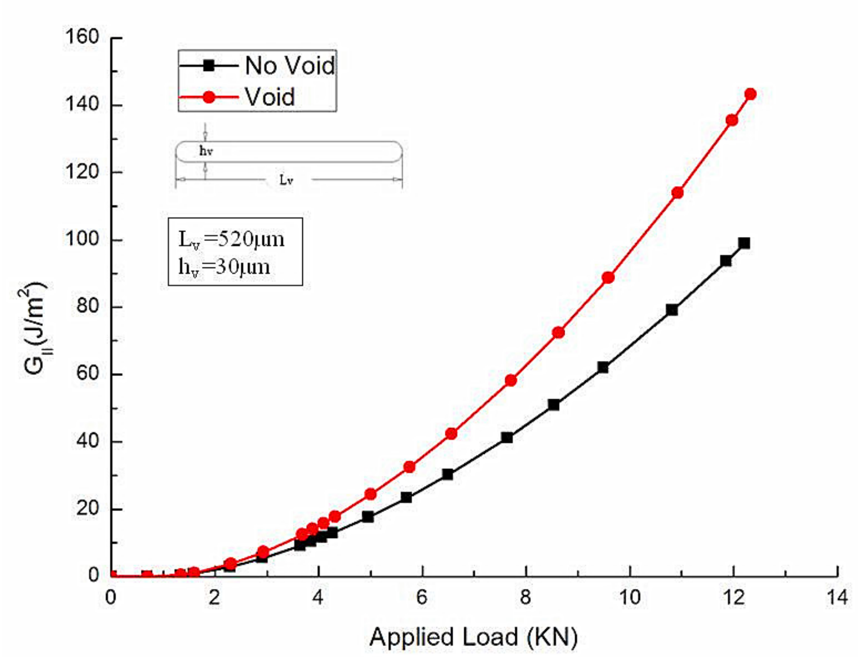


Fig. 34. Effect of void on Mode II SERR.

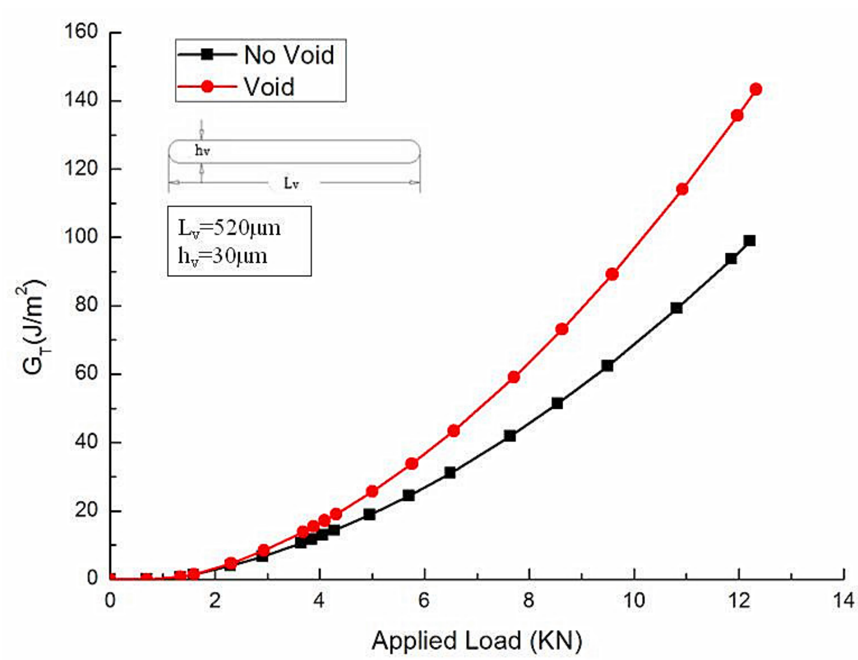
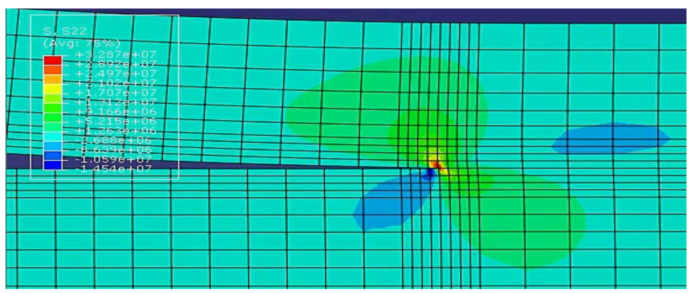
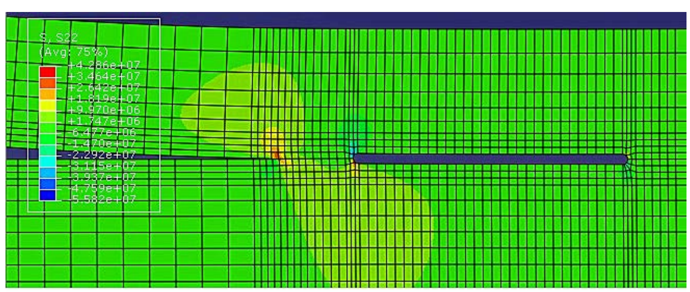


Fig. 35. Effect of void on Total SERR.

As previously discussed, the influence pattern of void on G_I could not be explained by the transverse displacement. We need to find another way to study the effects of void. From Fig.36 and Fig.37, it is clear that the both normal stress and shear stress fields near the delamination front are disturbed by the presence of void. As a result, it would be possible to explain the obtained SERR results through stress point of view. So if we look at the stress distribution along Y=0 (Fig.27) between the delamination front and the void, we could find that the presence of void change the normal stress distribution near delamination front and such perturbation becomes stronger when it comes closer to the void, as what is shown on Fig.38. Meanwhile, normal stress in the presence of void is lower than that in no void case. However, since normal stress near delamination front is much larger than that closer to void, the near delamination front region is thus more critical in the analysis. As a result, we only focus on the normal stress distribution of the region closer to the delamination front. From Fig.38, we can see that at 2.3KN applied load level, or before applied load reaches 4KN when G_I is yet to reach its maximum value as previously described, normal stress in the presence of void is slightly lower, and this corresponds to the finding on Fig.32 that G_I is slightly lower in the presence of void before it reaches its maximum value. At 4.0KN applied load level, we can see that normal stress is almost the same for both void and no void case, which corresponds to the finding that for both void and no void case, G_I reaches its peak value at almost the same applied load and has almost the same maximum value. Normal stress in the presence of void would be higher with further increase of applied load. This explains why G_I is higher for the void case after it reaches its peak value. Also, we could find an interesting fact through Fig. 38 that for both void and no void case, under certain applied load level, compressive stress is developed at a certain distance ahead of delamination front, which indicates that when the delamination grows to a certain length, compressive stress would be developed at the delamination front. Similar findings have also been confirmed by Whitcomb [18] for the no void case. As a result, it could be concluded that the presence of void would cause the perturbation of the stress field near delamination front, which makes delamination grow more easily.

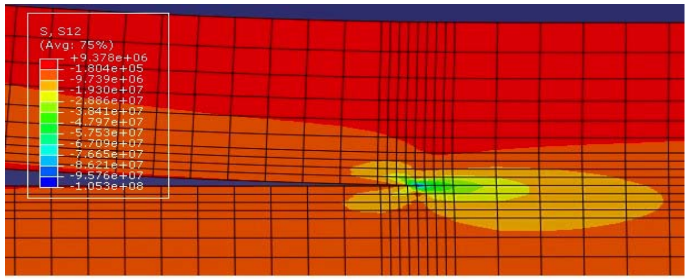


(a)

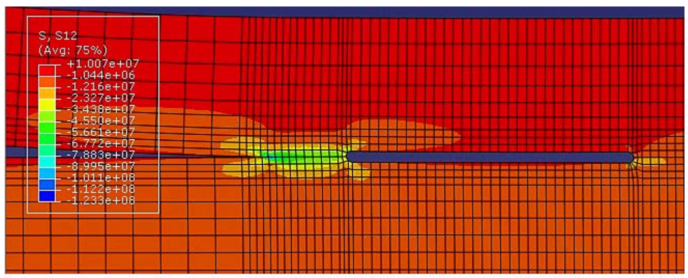


(b)

Fig. 36. Comparison of near delamination front normal stress contour at applied load=4KN (a) no void (b) with void.



(a)



(b)

Fig. 37. Comparison of near delamination front interlaminar shear stress contour at applied load=4KN (a) no void (b) with void.

Recently with the progress of related studies on voids, it has been realized that many factors such as void size, void shape and void distribution in the critical area should be considered in order to fully understand the effects of voids. As a result, in this research, two further studies were conduct to investigate the effects of void size and its location within the critical area on obtained SERR. Fig.40-Fig.42 show the comparison of obtained SERR between no void case and void of different elongation length. From Fig.40, we can see that before applied load increases to the level when G_I is the maximum, the presence of void has little effect on G_I value and effect of different size of void is barely found. In both cases, G_I follows the same trend with the increasing applied load and reaches its maximum value at the same applied load level. The only small difference is that the maximum G_I value is a little lower than the others in the case where void has the largest elongation length. However, we could not conclude this finding as a trend as the difference is very small, and since G_I is small in this study, even a small amount of difference would look significant. Once G_I reaches its maximum value, the effect of void becomes apparent with further increasing load. The presence of void increases G_I value, and the larger the void size is, the larger amount of increase is found. As what has been discussed, it is believed that the normal stress near delamination front would experience perturbation with the introduction of void, and this perturbation is only significant once the applied load reaches the level when G_I value is the maximum. For different size of void case, it is obvious that the larger the void size is, the stronger the perturbation is. Fig.41 and Fig.42 show that the presence of void would significantly increase G_{II} and G_T value even for a relatively small void. As could be expected, the larger the void is, the larger the increase amount is. This also indicates that compare to normal stress, the interlaminar shear stress near the delamination front is more sensitive to the void size.

Fig.43-Fig.45 shows the effect of void location on the obtained SERR. In this study, the most critical area is the region right ahead of delamination front. As a result, void was placed right ahead of delamination front but at different distances “d” from the delamination front. As can be seen on Fig.43, similar to all the previous G_I cases, the effect of void at a different location on G_I becomes relatively apparent only after G_I reaches its maximum value. However, no specific trend can be found this time and maximum value G_I decrease with increasing of distance within a certain distance and

then bounce back beyond that certain distance. The presence of void increases G_I is only found when the void is close enough to the delamination front. Beyond a certain distance, the presence of void decreases G_I. No satisfactory explanation can be drawn for this influence pattern on Fig.43. However, the trends for the effects of void at a different location on G_{II} and G_T are much clearer. As can be seen on Fig.44 and Fig.45, when the void is moving away from the delamination front, its influence on G_{II} and G_T becomes less and less significant. It should be noted that the effect of void is highly sensitive to its location within a certain distance. As what is shown on Fig.44 and Fig.45, there is a significant drop of obtained G_{II} and G_T value when the void is moved from 0.15mm away from the delamination front to 0.30mm, after that, further moving of the void shows little influence.

Finally, if we compare the obtained G_{II} value between Fig.41 and Fig.44, it is clearly that smaller void may have a larger influence that the larger void at more location further from the delamination front. This finding once again proves that when studying the effect of void on the properties of composites, many factors such as void size and location within the critical area should be considered and should not be considered separately.

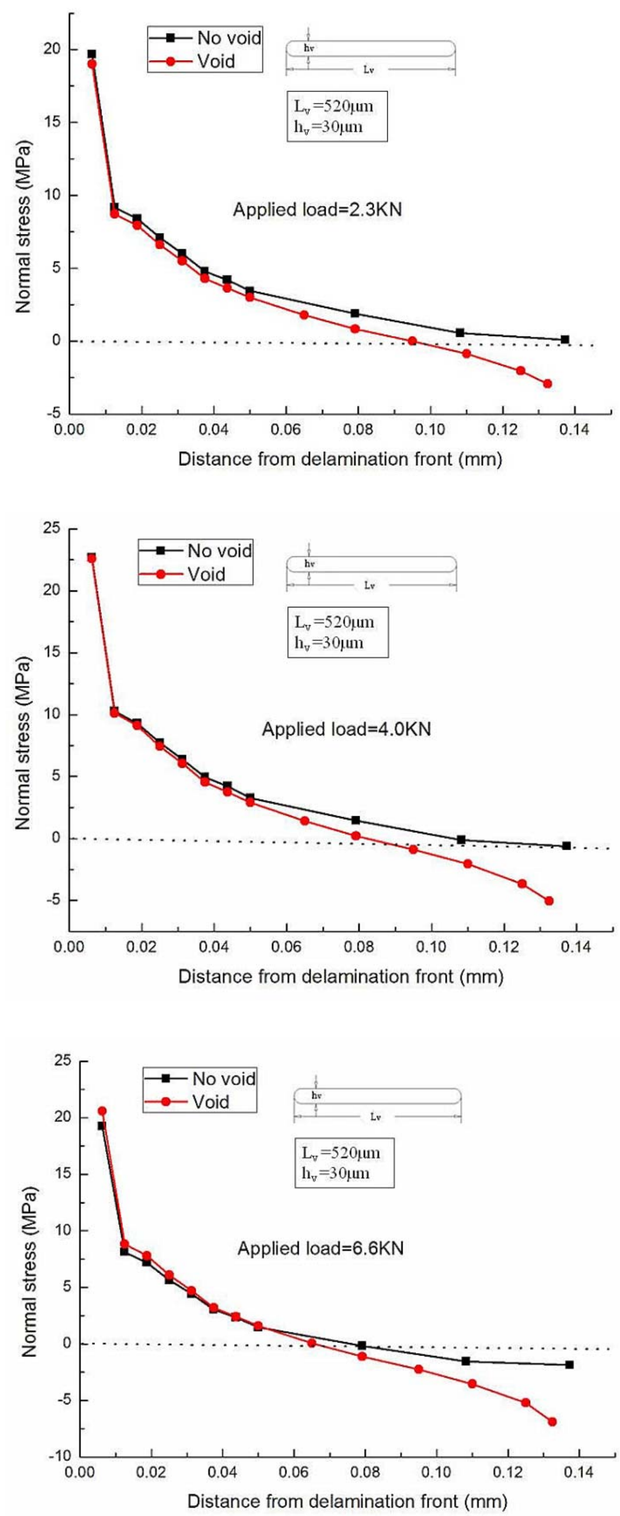


Fig. 38. Effect of void on normal stress between delamination front and void under different applied load.

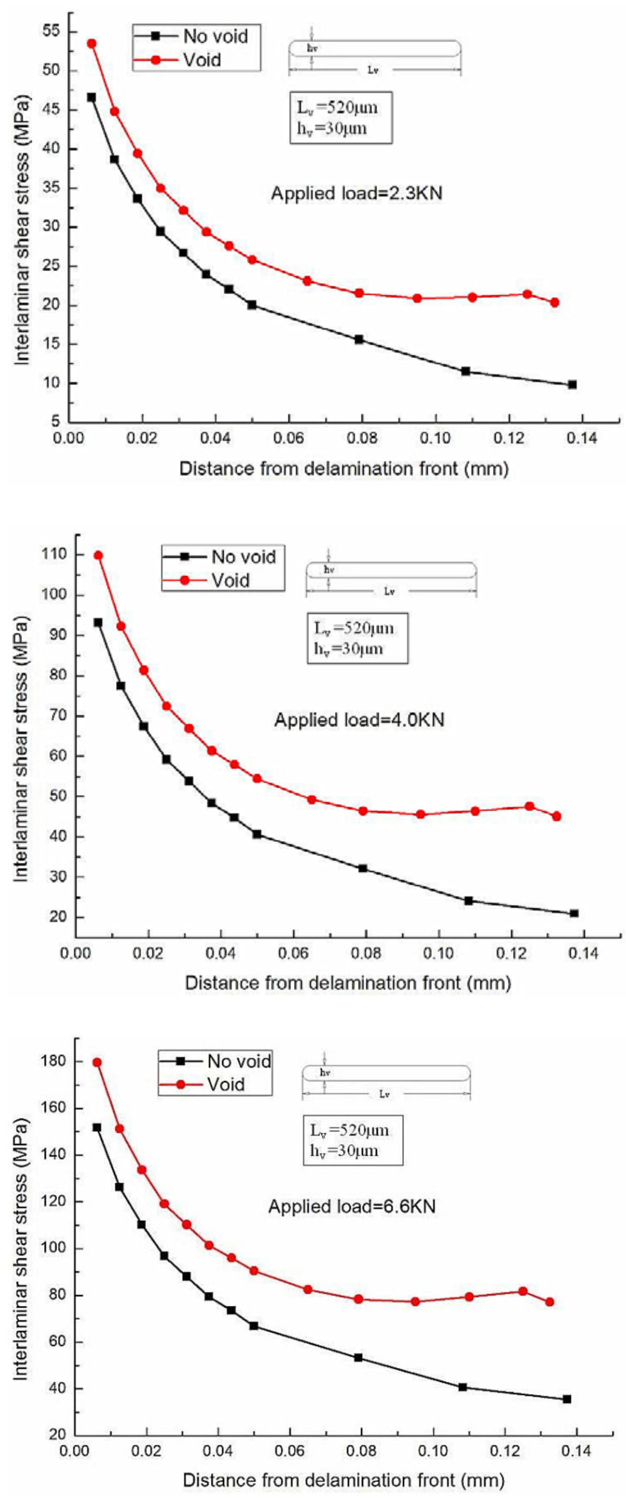


Fig. 39. Effect of void on interlaminar shear stress between delamination front and void under different applied load.

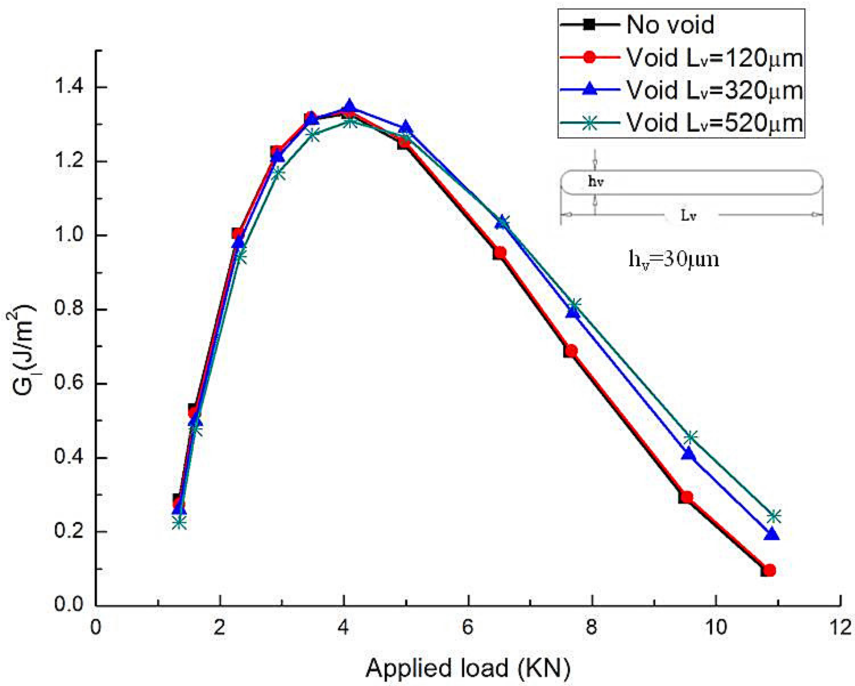


Fig. 40. Effect of void size on obtained Mode I SERR.

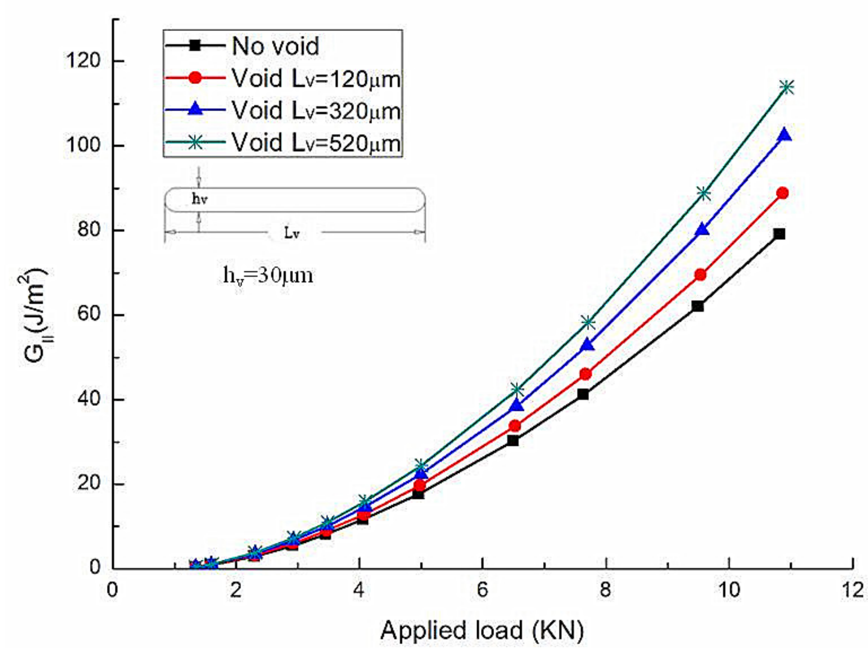


Fig. 41. Effect of void size on obtained Mode II SERR.

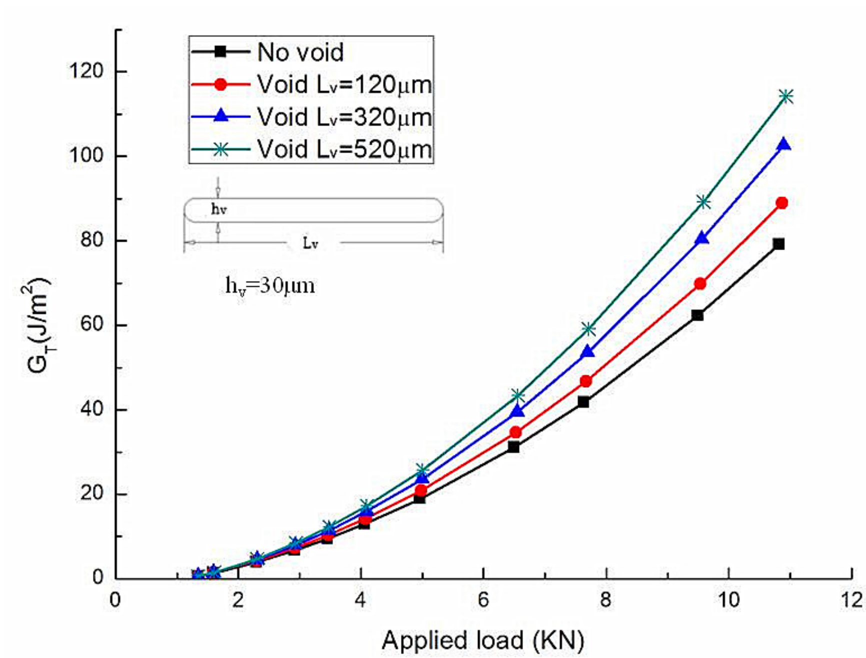


Fig. 42. Effect of void size on obtained Total SERR.

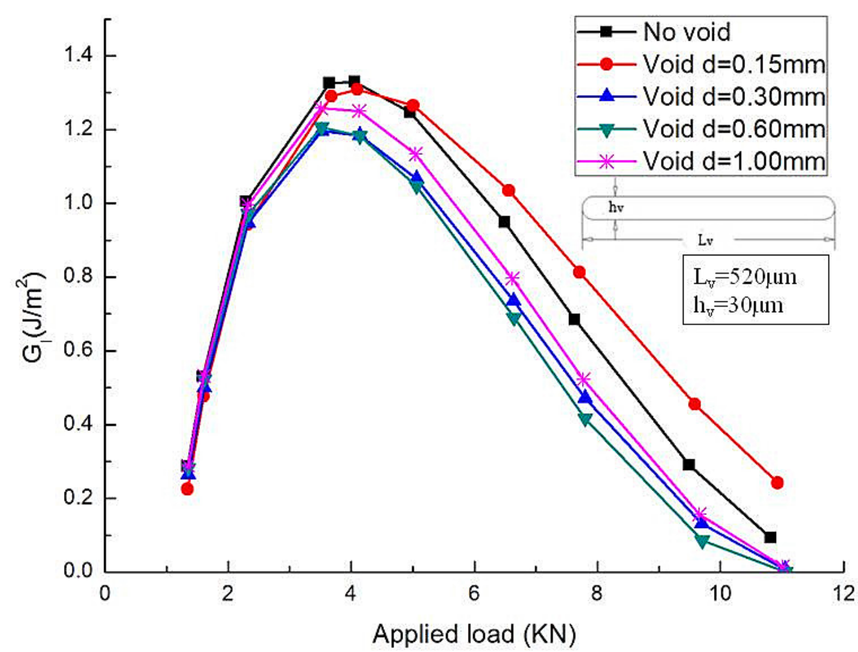


Fig. 43. Effect of void location on obtained Mode I SERR.

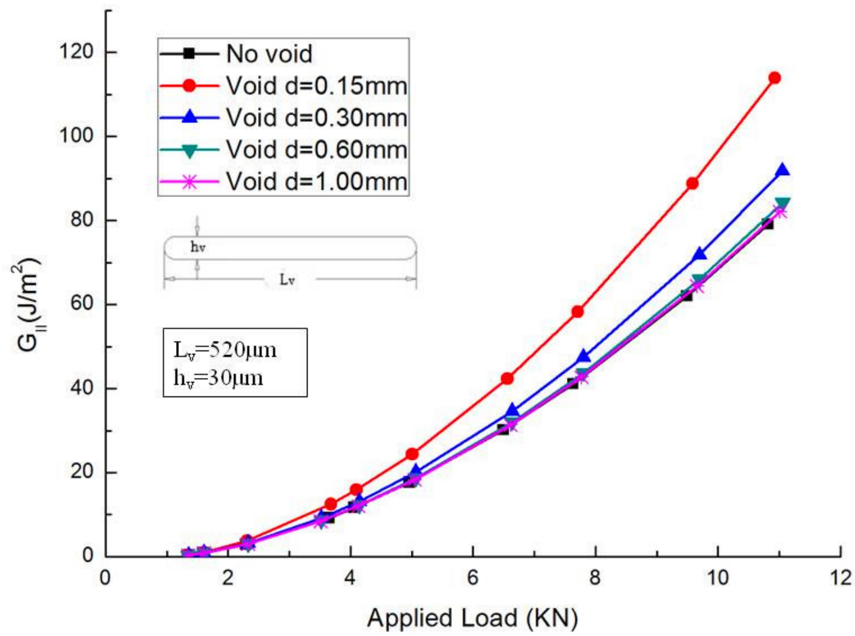


Fig. 44. Effect of void location on obtained Mode II SERR.

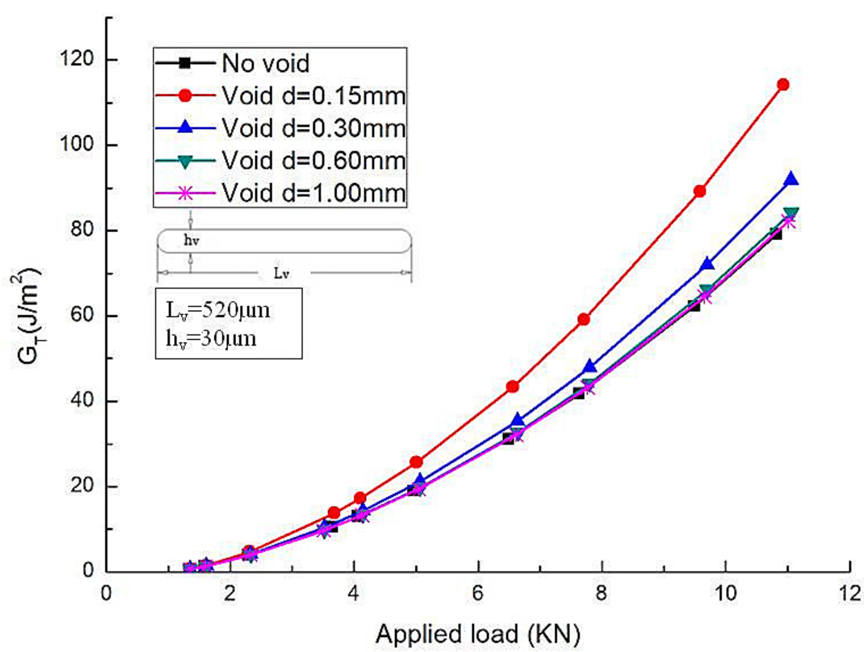


Fig. 45. Effect of void location on obtained Total SERR.

D. Summary

The effect of void on the post-buckling behavior of delaminated composite laminate under compression was investigated parametrically. The presence of void was found to disturb the stress field near delamination front and thus affect the obtained SERR. Based on the study, following conclusions can be drawn:

1. The presence of void has little effect on transverse displacement of delamination part.
2. The effect of void on G_I becomes apparent only after G_I reaches its maximum value. Different size and location of void may have different effects on G_I, however, no clear trend can be found in the current study for how does the location of void affect obtained G_I value.
3. The presence of void increases G_{II}. The larger the void size is, and the closer between void and delamination front, the larger amount of increase of G_{II} can be found.
4. Smaller void may have a larger influence than the larger void further away from the critical area.

CHAPTER IV

CONCLUSIONS AND FUTURE WORK

The primary goal of this study is to understand the effects of void on the surface delamination growth under compression. By considering different influence factors such as void size and its location within the critical areas, a basic trend of how does single void affect the delamination growth of compressively loaded unidirectional composites could be drawn. Current development of NDT techniques has made it possible to roughly detect the void size, shape and location. Once this information is obtained, the results produced in this study would help engineers better evaluate the durability of structure components. That is one of the contributions of this study.

The objectives of damage mechanics involve determining the initiation of damage, predicting the evolution of progressive damage. As a result, a comprehensive approach to understand the effects of voids should be able to account for their effects on the initiation of damage and progressive damage evolution process. Previous studies have experimentally proven that the presence of voids would affect the initiation and evolution of damage in composites under both static and fatigue loading [31, 35, 43]. Experimental findings could only provide us a direct impression of what are the effects of voids. However, they could not explain the mechanism behind these experimental results. Meanwhile, from technique point of view, it is difficult to conduct such experiments where voids have a certain size or shape and are located within the given areas. On the other hand, it is also costly to conduct all the experiments as a total understand of void effect requires a large amount of experiment data. As a result, parametric methods and theoretical methods serve as the best tools to study the effects of voids.

This study would serve as a piece in constituting a basic understanding of voids effect on the propagation of fracture or delamination events. Since it is a 2-D analysis, void is assumed to lie within the interface and across the whole specimen width, this determines that though the current model could provide useful results to predict the trend of how would void affect the delamination growth, a 3-D analysis is needed in order to produce more accurate results, and this requires for the abilities to detect voids in a 3-D sense and a large amount of computation time. Meanwhile, other issues such as different types of delamination and multiple voids case should be addressed in the future.

Unidirectional composite was discussed in this study as this type of composites is commonly used in the wind turbine blade structures and other structural applications. However, at the same time, many structures require composites to be designed with certain layups in order reach the optimized structural performance. Thus, it is important to account for effects of voids on composites with more complex layups.

The future research on the effects of voids should also focus on developing analytical approaches. Until now, only a few studies have tried to investigate the effects of void analytically, an analytical model that could account for general void situation would lift our understanding of voids to a higher level, which would also make computational results more convincing. All the works on this field would definitely benefit the future design of composite components in the long-term.

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