TRANSVERSE ZIGZAG DAMAGE MODE AND STITCH CRACKING IN ANTISYMMETRIC ANGLE-PLY LAMINATES

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ABSTRACT

A new damage type, called "transverse zigzag," is identified and studied, resulting in a finding that loads can "bypass" and "carry-through" regions of damage, depending on the geometry and laminate. This interactive damage mode, observed in experimental testing of single-edge-notched and double-edge-notched specimens, is not found reported in the literature. The mode is defined here to be "transverse zigzag" damage due to the visual appearance of the damage. A zigzag pattern can be seen on the side (through thickness) faces of specimens. The damage type is an interaction between matrix cracking and delamination, where matrix cracks occur between plies and are connected by small areas of delamination. Lengthscales associated with the transverse zigzag damage mode are identified.

1 INTRODUCTION

A damage interaction mode not found in the literature is reported based on experimental testing on single-edge-notched and double-edge-notched specimen testing. As documentation of such an interaction mode is not found in the literature, the mode is defined here to be "transverse zigzag" damage and is observed as an interaction between matrix cracking and delamination occurring through the thickness [1]. This terminology is used due to the visual appearance of the damage. The zigzag pattern can be seen on the side (through thickness) faces of specimens, with an example shown in Fig. 1. The damage type is an interaction between matrix cracking and delamination, where matrix cracks occur between plies and are connected by small areas of delamination. Reviewing the literature, the most similar damage type found is referred to as delamination "switching," where a delamination propagates along a ply interface and a matrix crack through a ply allows the delamination to "switch" to a neighboring interface [e.g., 2-4]. The delamination continues propagating along its original direction, but at a "switched" interface. However, unlike delamination "switching," the transverse zigzag damage mode propagates in a back-and-forth manner through the laminate thickness, resulting in a narrow band, ranging from 2 to 7 ply thicknesses in width, of damage in the through-thickness direction.

The results reported are a subset from a larger effort to characterize the constitutive response of composite materials [1, 5, 6]. Greater details on the specimens, experimental testing, damage characterization, and analytical investigation supporting this work are available in [1]. This paper introduces the transverse zigzag damage mode and the associated lengthscales that influence the mode.

2 TRANSVERSE ZIGZAG DAMAGE MODE DETAILS

Transverse zigzag is a combination of matrix cracking, stitch cracking (i.e., a type of matrix cracking), and delamination damage modes. These three modes interact to form the transverse zigzag damage type. The through-ply matrix cracks (of both the stitch cracks and the traditional matrix cracks) connect via delaminations between mismatch angle plies. In all experimental specimens exhibiting transverse zigzag, stitch cracking is present and was observed in the results of the computed microtomography investigations of the single-edge-notched and double-edge notched specimens. The transverse zigzag damage type is not found reported in previous literature. Literature on stitch cracking is very limited and fails to identify delaminations between ply interfaces. The previous studies that identify stitch cracking failed to look at damage in the through-thickness plane (i.e., x-z or y-z plane), so it is possible that transverse zigzag could have gone unnoticed. At the time stitch cracking was first identified and reported, the observable lengthscale [7] necessary to resolve this through-thickness damage mode was not sufficient. As the ability to resolve damage at smaller scales continues to improve, interactions occurring at smaller scales can studied.

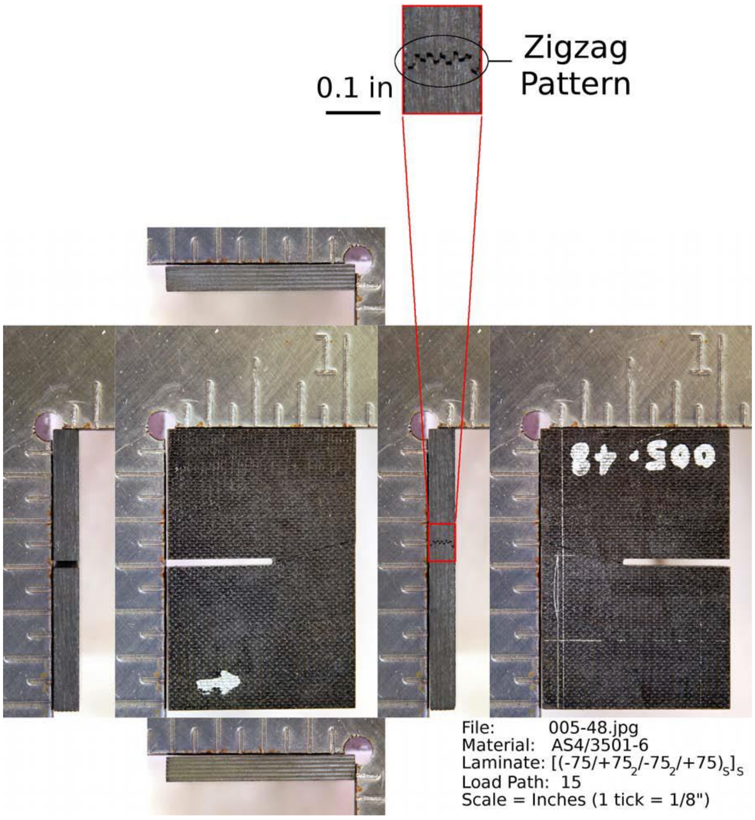

Figure 1: Documentation photograph layer of a single-edge-notched specimen (005-48) with transverse zigzag damage, with an enlarged view of a section of the right face where the zigzag path intercepts the edge.

The lengthscales [7, 8] involved with the interactions of damage modes involved in the transverse zigzag damage type include the laminate thickness, the normalized ply mismatch length, L, and the lengthscales associated with matrix cracking. In addition, new lengthscales are introduced from transverse zigzag: the “width” of the zig-zag pattern (i.e., in-plane length), the angle relative to loading, and the length of the propagation of the damage type. The results from the computed microtomography scans reveal that the transverse zigzag damage type propagates along fiber angles, maintaining the same zigzag shape, as shown in Fig. 1, along the entire propagation path.

3 EXPERIMENTAL SPECIMENS AND INSPECTION

The transverse zigzag failure mode is observed in two different experimental specimen types directly considered during this work. These are referred to as the single-edge-notched and double-edge-notched specimens. These specimen types each incorporate different structural details, allowing investigation of lengthscale effects that arise as the levels of composite testing are maneuvered. The single-edge-notched and double-edge-notched specimens provide a baseline characterization for the material used during this study. These specimens have relatively simple geometries. The higher levels of testing, not included in this paper, include specimens with an open hole and the specimens with ply drop-offs. These specimens represent an increase in structural complexity from the baseline characterization tests and allow an investigation of how the mechanisms controlling damage are affected at an increased structural level. In particular, the inclusion of the structural details, the open hole and the ply drop-offs, change the stress-field gradients within the structure, and thus the material. These gradients can change the forcing lengthscale, and introduce the possibility of inducing damage mechanisms and interactions associated with different lengthscales. Details of the open hole and ply drop-off specimen are included in [1]

For the transverse zigzag damage mode, which is the topic of this paper, only five open hole specimen were observed with this damage mode and no ply drop-off specimens exhibited the mode. Thus, these two specimen types are not discussed herein. The geometric dimensions and structural detail of the single-edge-notched specimen and double-edge-notched specimen are shown in Fig. 2, respectively, with the specifics of the specimens further described in sections 4.1 and 4.2 of [1]. Dimensions listed in are nominal and are given in the system in which they were manufactured. The single-edge-notched specimens were manufactured for a previous study using English units. The double-edge-notched specimens were manufactured using SI (International System) units.

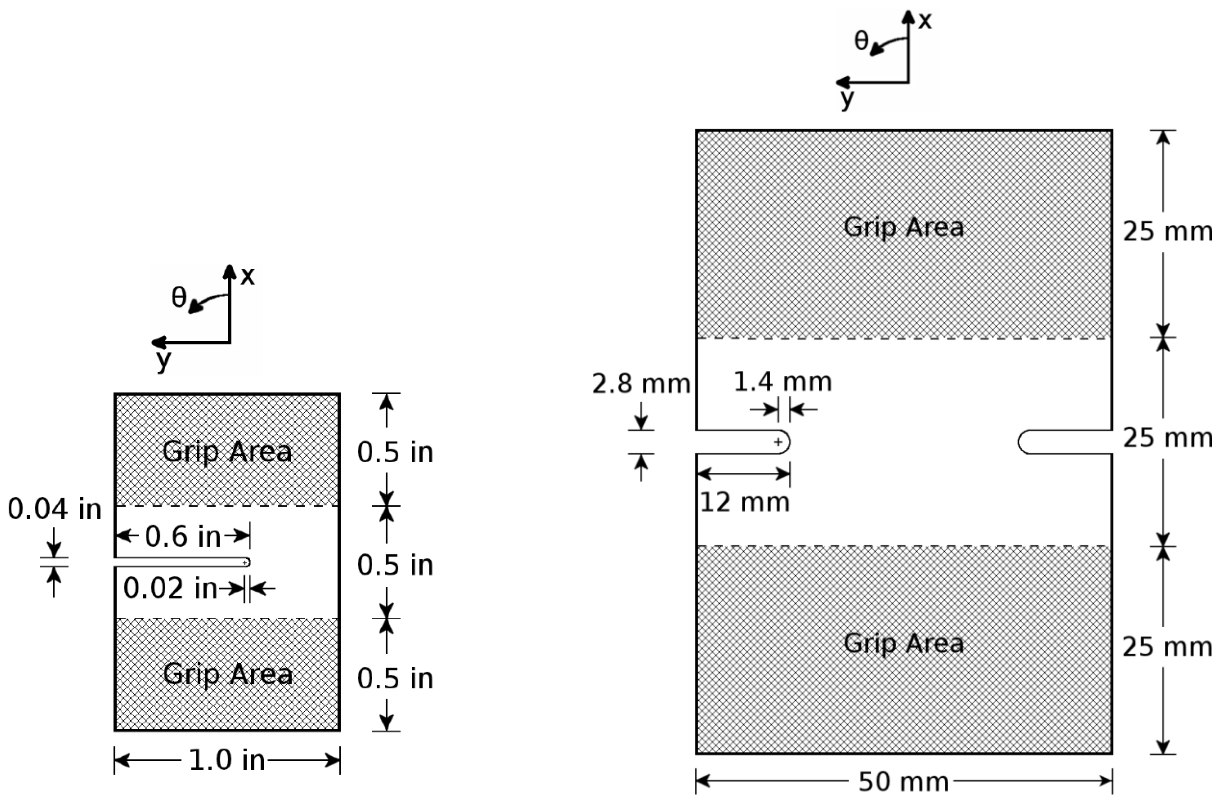

Figure 2. Planar illustration of the (left) single-edge-notched specimen and the (right) double-edge-notched specimen.

All specimens are manufactured and tested by collaborators at the NRL (Naval Research Laboratory) in Washington D.C., U.S.A., and the CRC-ACS (Cooperative Research Centre for Advanced Composite Structures) in Victoria, Australia. The single-edge-notched specimens are made of AS1/3501-6 carbon/epoxy and the double-edge-notched specimens are made of AS4/3501-6 carbon/epoxy. The only difference between the AS4/3501-6 and AS1/3501-6 material is the fiber used to form the preimpregnated unidirectional plies. The AS1 and AS4 fibers have almost identical mechanical properties (i.e., Young's modulus, fiber diameter, density), with the main difference being that the AS4 fibers have a 40% increase in tensile strength over the AS1 fibers [9-11]. The single-edge-notched specimens are made with $[(-\theta/+\theta_2/-\theta_2/+\theta)_S]_S$ angle-ply laminates and the double-edge-notched specimens are made with $[+\theta/-\theta]_{16T}$ and $[+\theta_4/-\theta_4]_{4T}$ angle-ply laminates. In both specimen types, laminate angles with θ equal to 15°, 30°, 60°, and 75° are investigated.

All specimens are documented postmortem. The goal of the damage documentation procedure is to fill a void in the testing of composites by establishing a unifying method for documenting and reporting damage in specimens. The developed procedures offer ways to compare damage both qualitatively and quantitatively, and allow lengthscale effects to be better investigated across the levels of composite testing. The damage documentation procedure is detailed in depth in Section 5 of [1]. The procedure begins by documenting the specimen faces with an optical photograph layer (e.g., Fig. 1), followed by quantifying the damage extent using a damage grid layer, and finally creation of damage sketch layer to capture the type(s) and orientation of damage. At the time of this study, each step was completed manually by the investigator, a very labor intensive and subjective process. As computer vision and artificial intelligence methods have advanced, it is highly recommended to automate the procedures. This would save a tremendous amount of time processing each specimen and enable an objective classification procedure. The base documentation photographs of this work can be made available to researchers developing such capabilities. While all specimens are documented following this procedure, select specimens were chosen to be investigated via X-ray micro-focus computed tomography (μCT). The μCT inspection technique demonstrates a leap in observable lengthscale, enabling damage to be investigated throughout the volume of a specimen at resolutions of a few microns. Also, the resulting digital volume enables artificial intelligence methods to be developed in order to process the postmortem damage characteristics [e.g., 12].

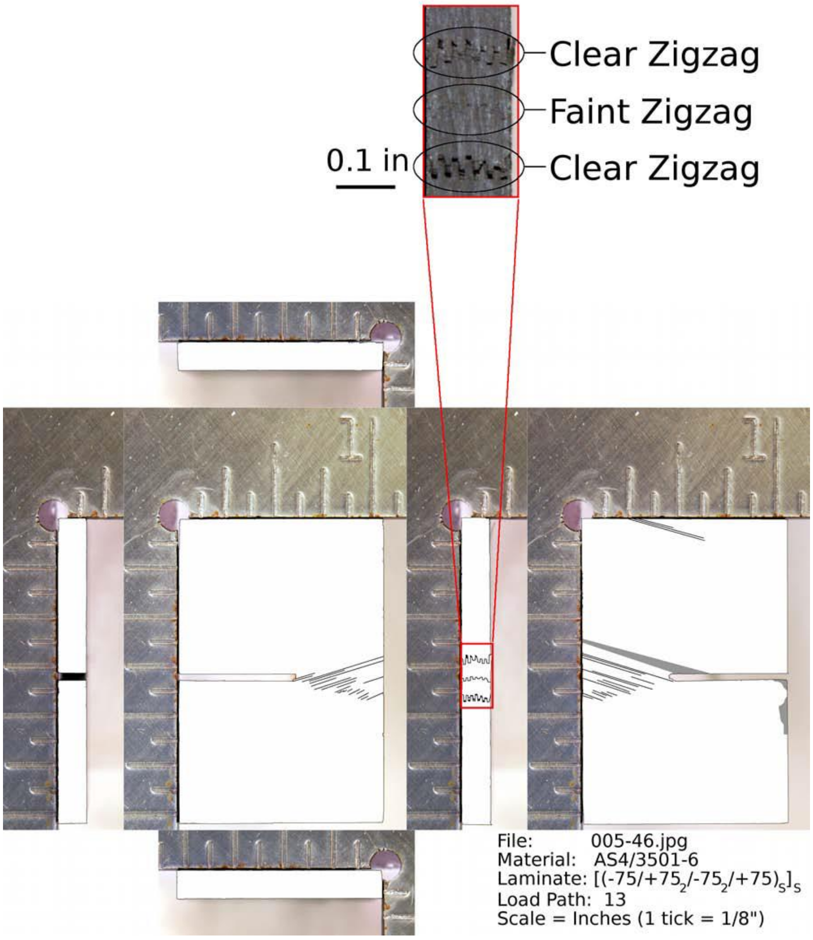

Figure 3. Example damage sketch layer of a single-edge-notched specimen (005-46) with multiple transverse zigzag damages, with an enlarged view of a section of the right face where the transverse zigzag paths intercept the edge.

4 DISCUSSION

The interaction of key lengthscales due to structural features (i.e., those associated with structural details resulting in stress and strain gradients), and the key lengthscales associated with damage initiation drives the damage type present within composites. Within the single-edge-notched and double-edge-notched specimens, the notch geometry coupled with the loading result in stress and strain gradients that initiate and then propagate damage.

This transverse zigzag pattern is observed in 52 of the single-edge-notched specimens, with the damage initiating at the tip of the strain riser and progressing along the fiber angles to a side surface. Almost half (24 specimens) of the specimens exhibiting this transverse zigzag pattern have a fiber angle of 75°, 10 specimens have a fiber angle of 60°, 11 specimens have a fiber angle of 30°, and the remaining 7 have a fiber angle of 15°. The surface to which the transverse zigzag propagates depends on the fiber angle of the laminate, as the propagation path starts at the tip of the strain riser and follows the fiber angle to the intercepting edge. Of those specimens exhibiting transverse zigzag, 10 specimens have multiple transverse zigzags present, while the other 42 specimens have only a single transverse zigzag. The damage paths in specimens with multiple transverse zigzags are always symmetric about the strain riser (i.e. the y-z plane). The example shown in Fig. 3 has a transverse zigzag damage that is symmetric about the strain riser. In the enlarged portion of the figure, two distinct transverse zigzags are present (labeled as "clear zigzag"), and upon closer inspection, a faint third transverse zigzag can be found (labeled as "faint zigzag").

Transverse zigzag damage similar to that seen in the single-edge-notched specimens is observed in the double-edge-notched specimens. A single transverse zigzag damage is observed in 171 of the specimens, while only 2 specimens exhibit a double transverse zigzag damage. The initiation point for transverse zigzag damage is always at the tip of one of the notches, with the damage progressing along the fiber angle until intercepting a specimen edge. Unlike in the single-edge-notched specimens, one of the two double transverse zigzag damage paths is not symmetric about the notch direction. The one specimen with unsymmetric (about the y-z plane) transverse zigzag damage has a single zigzag initiating from each notch tip. The photograph and damage sketch layers of this specimen are shown in Figs. 4 and 5. The two damage paths progress along the fiber angles and cross at the centerline of the specimen. Minimal interaction between the two damage paths is apparent from the visual damage. Both paths appear to be unaffected by the other path, continuing along their original direction while crossing. Further investigation of the damage paths of this specimen was conducted using computed microtomography. Virtual section cuts taken near the mid-plane of each ply are shown in Fig. 6, illustrating the unaltered paths when the two zigzag paths cross. The other specimen with a double zigzag had both transverse zigzag damage paths originate at the same notch tip, similar to the transverse zigzag damage seen in the single-edge-notched specimens.

It was found that the normalized characteristic lengths, l_5 and l_{10}, corresponding to the strain fields returning to within 5% and 10% of far-field strain, of the double-edge-notched specimens are related to the presence of the transverse zigzag damage type [1]. The characteristic lengths of the laminates of the double-edge-notched specimen, as determined by finite element studies not included here, are listed in [1]. These results are from the analysis of the double edge-notched specimen loaded in pure tension. It was found that the characteristic length increases as the ply angle increases. For laminates with θ equal to 60° and 75°, the characteristic lengths are greater than the distance from the notch tip to the centerline of the specimen. The experimental results of the double-edge-notched specimen from the comparison database, show that the transverse zigzag damage type is present in exactly half of the specimens tested. The half with the transverse zigzag damage type present correspond to the laminates with θ equal to 60° and 75°. Thus, in order for the transverse zigzag damage type to develop and propagate, the gradients of the stress and strain fields must be low (i.e., slowly changing fields). Within the experimental results of the laminates with θ equal to 15° and 30°, the transverse zigzag damage type was not present. For these laminates, the characteristic length, l_{10}, was determined from the results of the finite element models to be 0.7 and 5.4 (measured as the number of notch radii from the edge of the notch), respectively [1]. For these laminates, the resulting strain fields due to the structural feature create unfavorable conditions (i.e., the strain fields do not initiate the damage mode) for the development of the transverse zigzag damage type.

Figure 4. Optical documentation photographs of a double-edge-notched specimen (CH-C601-0704).
(Note: Region between dashed lines represents material volume scanned with μCT)

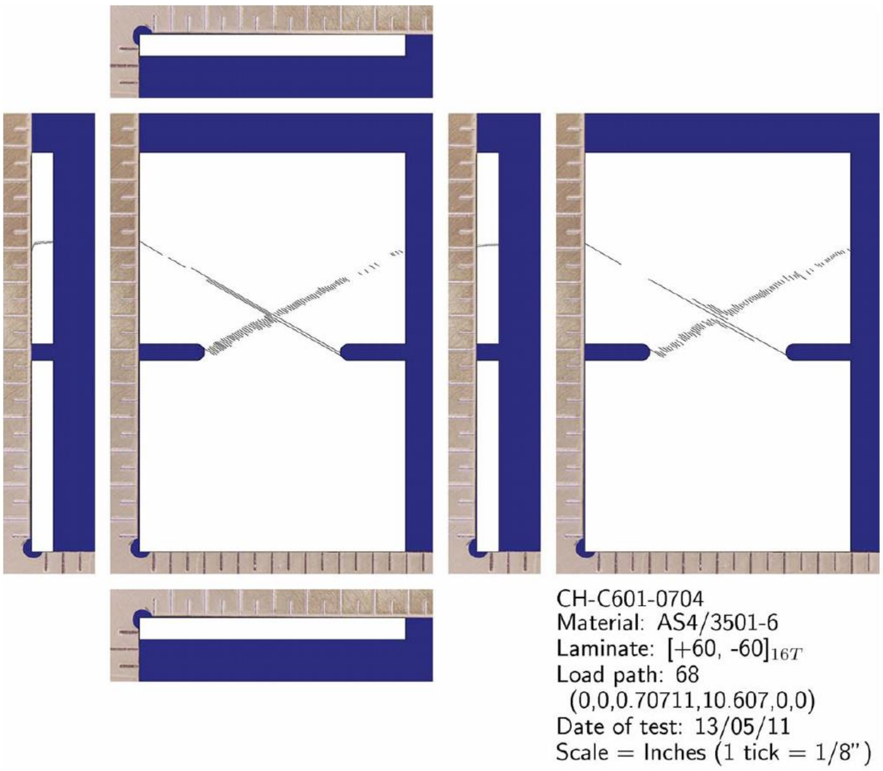

Figure 5. Damage sketch of a double-edge-notched specimen (CH-C601-0704) exhibiting crossing transverse zigzag damage.

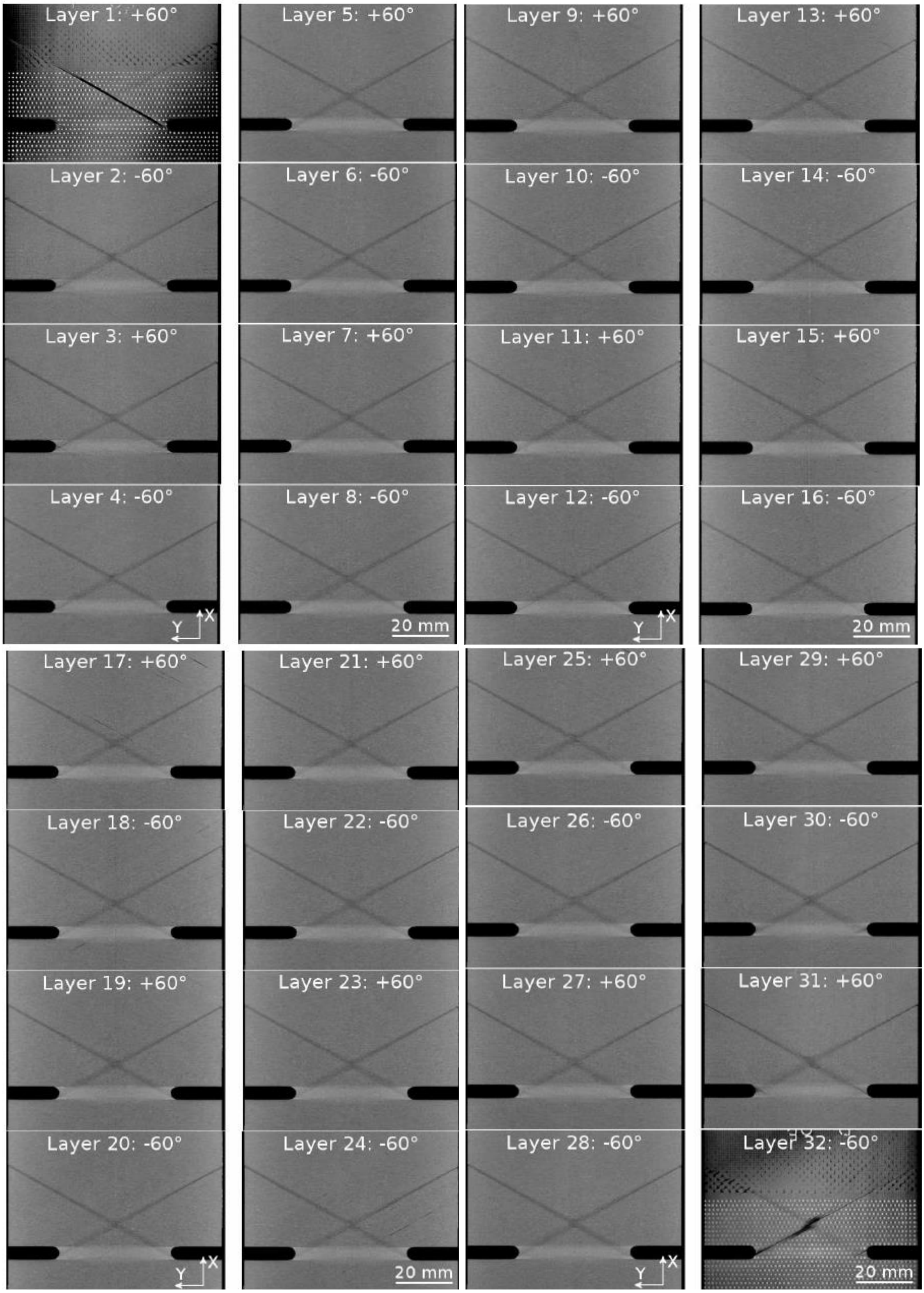

Figure 6. Multiple virtual section cuts of a double-edge-notched specimen (CH-C601-0704), showing 'front' views with virtually removed material (sectioned) from the first ply to the last ply.

5 CONCLUSIONS

A unique damage type and associated lengthscale interaction discovered during experimental testing involves the "transverse zigzag" damage type which is an interaction of matrix cracking, stitch cracking, and delamination. The lengthscales involved with the interactions of damage modes involved in the transverse zigzag damage type include the laminate thickness, the normalized ply mismatch length, L_γ, and the lengthscales associated with matrix cracking [7]. In addition, new lengthscales are introduced from transverse zigzag: the "width" of the zig-zag pattern (i.e., in-plane length), the angle relative to loading, and the length of the propagation of the damage type. The results from the μCT scans reveal that the transverse zigzag damage type propagates along fiber angles, maintaining the same zigzag shape along the entire propagation path. Therefore, the lengthscales influencing the damage type propagate with the type, but do not change as the type propagates.

In order for the transverse zigzag damage type to develop and propagate within laminates, the gradients associated with the stress and strain fields due to a structural feature must be slowly changing. The normalized characteristic lengths of specimens with the transverse zigzag damage type present are always greater than those of specimens lacking the damage type. The resulting strain fields of structural features with relatively short normalized characteristic lengths are an indication that an unfavorable strain field is present and damage modes will not interact to initiate and propagate the transverse zigzag damage type.

Lengthscales associated with gradients in the strain fields near matrix cracks are dependent on the orientation of the crack relative to the loading direction. For the specific case of the stitch crack damage type, load was observed to "bypass" and "carry-through" the damaged region. The "bypass" of load corresponds to the reduced capability of load paths through the region of damage, requiring load to pass around the region while some load is carried across the intact portion of the damaged region. The amount of load "bypass" increases with laminate angle due to the details of the geometry of the stitch cracks with the region of damage causing greater reduction of load-carrying capability as the laminate angle increases. Thus, the ability to "carry-through" load is dependent on the laminate angle which influences the orientation of the details of the damage relative to the applied loading.

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In memory of Professor Paul A. Lagacé. His impact on composites lives on through his students.

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