ADHESIVELY BONDED COMPOSITE DURABILITY (ABCD) PHASE 3

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ABSTRACT

The Adhesively Bonded Composite Durability (ABCD) program is a multi-phased effort by the Office of Naval Research (ONR) to address the concerns of bonded composite joints as major structural load paths. The initial phase of the program performed a gap analysis on current material methods and analysis technologies that would support the design guidelines of the Joint Service Specification Guide (JSSG-2006). Phase 2 advanced two of the items identified in the gap analysis, a fail-safe life limit (FSLL) analysis and the further development of allowable test methods to support bonded primary joints. The current phase 3 of the program focuses on closing the gaps in the two selected areas of the prior phase. The FSLL efforts will address the assumptions built into the analysis, such as the use of Miner's rule and fatigue crack growth characteristics like path, shape, and mode mixity. This will be achieved through the fatigue testing and analysis of a bonded element that incorporates many aspects of a joint seen in aircraft design. An additional goal of the analysis in this phase is display the ability to determine the residual strength of the bonded joint after it has experienced a determined amount of life. The allowable test method development effort will include maturation of a Mode II fatigue test to determine fatigue delamination onset and growth characteristics, maturing a Mode III test method, developing mixed mode crack growth data that incorporates mode III effects, and overall interlaminar fracture testing of fabric materials in all failure modes.

1. INTRODUCTION

Phase 1 of the ABCD program consisted of a gap analysis and a cost benefit analysis of technologies necessary for the certification of durable bonded composite structures. Analysis technologies, methods, and material data sets were evaluated to identify their current capabilities and where they were deficient to meet the certification language in the Joint Services Specification Guide [1]. The gaps identified were then subjected to a cost benefit analysis which provided a rating based on high/low payoff and high/low cost. With those results, two technologies, B-Basis Allowables Development and Fail-Safe Life Limit (FSLL) Analysis, were given a result of high payoff and low cost. These were selected for continued study in ABCD Phase 2

Phase 2 of the ABCD program had the goal of advancing the B-Basis Allowables of bonded composite materials by first understanding the FSLL analysis input requirements. Then developing the test methods to support those input requirements and developing the data

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reduction methods necessary. Phase 2 efforts saw testing completed to determine Mode II, and III static crack growth data as well as Mode II fatigue crack growth data (cycles to onset and da/dN) for a graphite/epoxy fabric material. These were material properties that were required for the FSLL analysis inputs.

Phase 2 also had the goal of advancing the analysis capability to determine a fail-safe life limit of a bonded composite joint subjected to fatigue cycling. First, the capable commercial progressive damage analysis (PDA) methods were evaluated to determine their capabilities and try to map what the output was to the current certification language. The result of that study was that the current fatigue PDA methods were severely lacking and required excessive analysis times. A parallel effort led to the development of an in-house fatigue routine that would calculate interlaminar fatigue crack growth based on FEM computed strain energy release rates. The developed method, called CFATIGUE, is shown in Figure 1.

This routine required a detailed FEM to be analyzed beforehand that would capture the crack growth behavior of the composite joint under monotonic static loading. A directional strain energy (Gi) response at a crack tip as a function of load was then extracted from the static analysis results for all three modes. This joint data along with the load spectrum, modal cycles to onset of crack growth and modal crack growth rates was required to run the analysis. The analysis would start off by determining the minimum and maximum loads for the first cycle. Then, it would look up the individual modal strain energies at the crack tip based on the extracted FEM data. With the strain energies known in each mode, it would then determine either the cycles to onset or the crack growth rate for each mode. Then it would perform a mode interaction to determine a mixed mode cycles to onset or crack growth rate value. If the crack was actively growing, then it would update the crack length to incorporate the amount of crack advancement seen in that cycle. If the crack growth had not initiated, then it would store the cycles to onset value following a Miner's rule of damage accumulation. Then it would proceed to the next cycle where the process would repeat until one of two conditions were met. The analysis would stop when it exceeded the crack length data provided by the static FEM solution or it completed all prescribed cycles. The routine would generate a cycle-by-cycle history of applied loads, crack length, modal and interacted strain energies, failure to onset data, and crack growth rates.

During the development of the routine, several theories were implemented into the routine for interacting the modal data to determine a singular value of cycles to onset or crack growth rate for a given cycle. Cycles to onset received two theories. One was an implementation that followed the BK Law of mode mixing [2] used in static linear elastic fracture mechanics analysis. The other was called the resistors in parallel method shown below:

$$N_{Onset} = \frac{1}{\frac{1}{N_{Onset,I}}+\frac{1}{N_{Onset,II}}+\frac{1}{N_{Onset,III}}}$$

The crack growth rate interaction determination received three theories. One followed the BK Law of mode mixing, the second followed a linear interaction, and the third considered only the maximum growth rate direction.

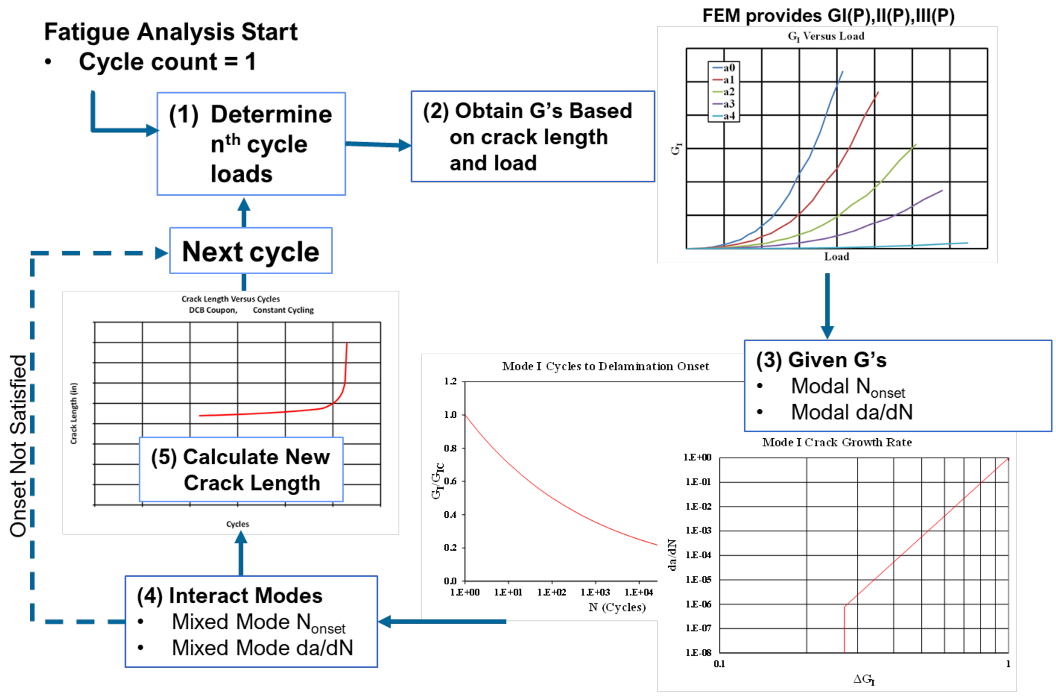


Figure 1: Interlaminar Fatigue Crack Growth Analysis Routine

One of the goals of the Phase 2 FSLL effort was to compare the analysis performed to test data for validation of the tool. It was found that the availability of applicable, mixed mode fatigue crack growth test data for bonded composite joints was limited. A parallel effort was generating this sort of data for another project, however, it was noted that the goals of that project were not in line with the data requirements of this program, so the recorded data and even the test configuration were not ideal to be used. The bonded composite joint was an I-beam that was composed of the caps bonded to the web using a pi-preform. The joint was subjected to spectrum fatigue loading with some in-situ determination of the crack length. The data from this test configuration was used as a start to validate the analysis method described above. The static FEM can be seen in Figure 2, as well as the CFATIGUE output for crack length vs cycles compared to the measured test data. The resulting crack growth rates under predicted the test data in general.

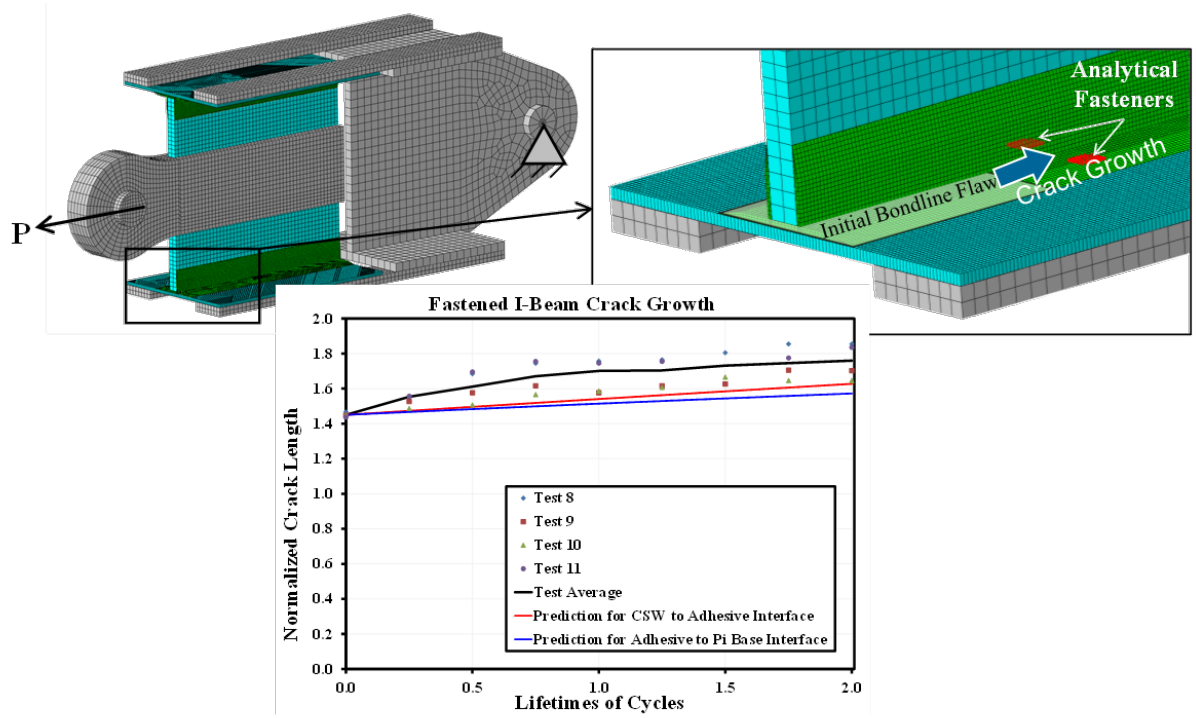


Figure 2: Interlaminar Fatigue Crack Growth Routine Results Comparison

Phase 2 of ABCD concluded with another gap analysis of the B-Basis Allowables Development and FSLL efforts. The following gaps were identified:

- Finite Element Analysis Validation
  - Limited validation of the I-beam FEM.
  - I-beam analysis predictions under-predicting test data.
- Residual Strength
  - Residual strength at hot/wet conditions.
  - Interaction with multiple failure modes in presence of significant damage
- Method Validation
  - Validation of mode interaction methods
  - Expand to additional mode-mixities
  - Damage accumulation methods for composites
  - Validation of delamination fatigue onset predictions
  - Differences fatigue analysis models require further study.
    - 2 onset, 3 growth
- Testing
  - Large scatter in Mode II onset, and da/dN crack growth data
  - Testing of bonded assemblies or individual constituents
  - ILF testing of fabric (all fracture modes) is not yet mature
  - Static mode III test method requires further development
  - Mode II fatigue delamination onset, and fatigue delamination growth testing maturity
  - Mixed-mode testing and Mode III fatigue were not addressed

    - B-Basis allowables development and fatigue curve back-off factors

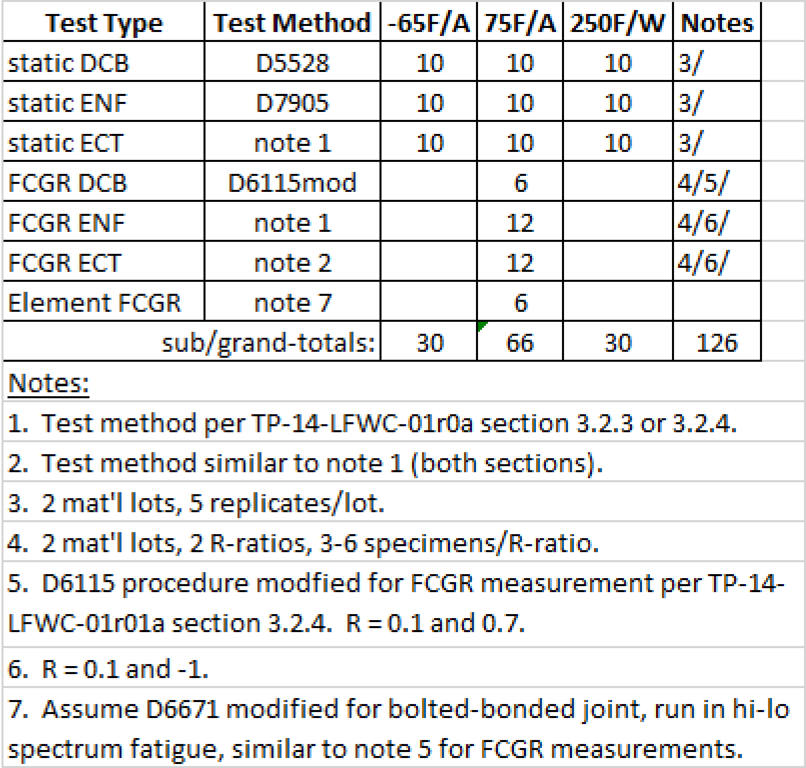
Phase 3 of the ABCD program has the following objectives:

- Develop and execute test plan to address phase 2 gaps
    - Mode I, II, III testing of fabric composite laminates
    - Sub-element fatigue test to be used for model validation efforts
- Review and refine methodology developed in phase 2
- Provide additional validation of methodology
    - Incorporating updated properties
    - Develop a sub-element model to compare in fatigue
    - Review original assumptions

2. B-BASIS ALLOWABLES DEVELOPMENT

The phase 3 B-Basis allowables development began to address the phase 2 gaps by generating a test matrix to continue the static and fatigue testing of fabric composite laminates. Table 1 shows the planned test matrix and the associated test method. Most of the planned test specimens were assigned to static testing at different environmental conditions. Fracture and fatigue crack growth rate testing was also planned for all three modes at room temperature conditions, with most of the focus being directed at Modes II and III.

Table 1: B-Basis Allowables Development Test Matrix



Test Type	Test Method	-65F/A	75F/A	250F/W	Notes
static DCB	D5528	10	10	10	3/
static ENF	D7905	10	10	10	3/
static ECT	note 1	10	10	10	3/
FCGR DCB	D6115mod		6		4/5/
FCGR ENF	note 1		12		4/6/
FCGR ECT	note 2		12		4/6/
Element FCGR	note 7		6		
	sub/grand-totals:	30	66	30	126

Notes:

1. Test method per TP-14-LFWC-01r0a section 3.2.3 or 3.2.4.
2. Test method similar to note 1 (both sections).
3. 2 mat'l lots, 5 replicates/lot.
4. 2 mat'l lots, 2 R-ratios, 3-6 specimens/R-ratio.
5. D6115 procedure modfied for FCGR measurement per TP-14-LFWC-01r01a section 3.2.4. R = 0.1 and 0.7.
6. R = 0.1 and -1.
7. Assume D6671 modified for bolted-bonded joint, run in hi-lo spectrum fatigue, similar to note 5 for FCGR measurements.

The edge crack torsion (ECT) test specimen was selected for Mode III static and fatigue testing. Figure 3 shows the ECT specimen and configuration. The methodology to reduce the data for calculation of static Mode III fracture toughness (G_{IIIC}) was also investigated. A multi-step process was outlined which involved conducting the toughness test, a shear modulus test of the sublaminate, and a system compliance test. These test results were then used to calculate various compliances of the entire test system. For example, the compliance of the system was calculated from the load-displacement curve of the system compliance test. The specimen compliance was determined from the load-displacement curve of the toughness test. The sublaminate compliance was determined from the load-displacement curve of the shear modulus test. Finally, the system compliance calculations are used with the maximum load from the toughness test and some of the physical measurements of the test coupon to calculate the Mode III fracture toughness.

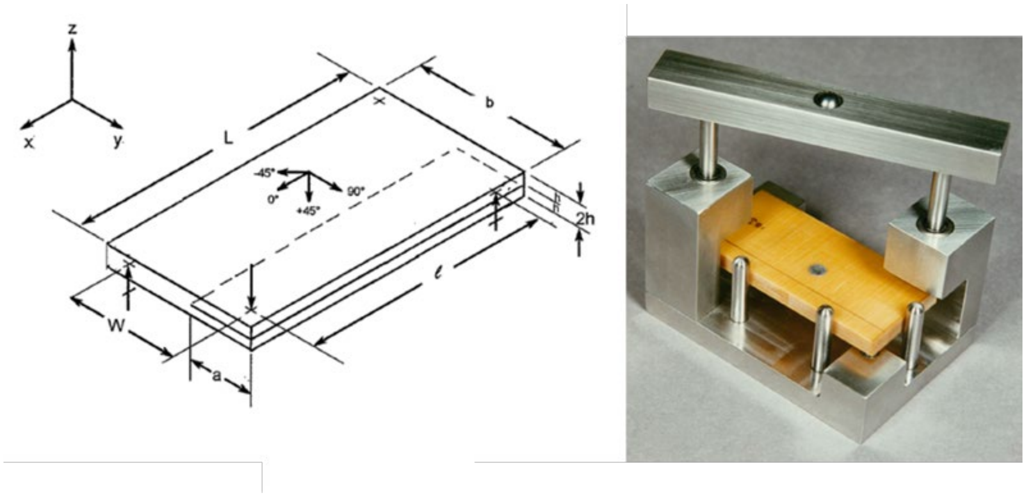


Figure 3: ECT Test Specimen and Fixturing

The test method for using the ECT specimen in fatigue was also developed to determine cycles to onset and crack growth rate of the graphite epoxy fabric material in Mode III crack growth. The test method would largely follow the FCGR test method used in Mode I and II testing with some specific clarifications and changes. The in-situ crack length/area determination would be completed by specimen compliance calculations, and other means of crack growth detection would be optional. After the test, visible crack length increments would be measured. When conducting the test, the onset of crack growth portion of the test would be conducted in the same manner as the Mode I and II testing. After onset was achieved, the crack growth rate portion of the test would follow the general procedure outlined in ASTM E647 [3], where section 8 outlines several procedures determining the crack growth rate data. The lab would be free to select the procedure it determines to be most suitable to generate the required output curves.

3. FAIL SAVE LIFE LIMIT ANALYSIS METHODOLOGY

3.1 Static Analysis Accuracy and Validation

The software selected to perform the VCCT FEM analysis for the FSLL-CFATIGUE routine was ABAQUS due to the implementation of automatic crack growth and the ability to extract the directional strain energies at the crack tip. The VCCT routine utilized during the development of the CFATIGUE routine lacked an overall robustness which required complicated modeling techniques to obtain a solution that captured significant crack growth and load redistribution (ABAQUS v6.14). In recent years, significant effort and analysis advancements have been implemented into the ABAQUS VCCT solution which have increased the robustness and stability of the code. The analysis advancements have also been accompanied by a significant verification and validation effort along with the development of modeling guidelines. By utilizing the latest releases of ABAQUS, improved static analysis correlation to test data is expected.

3.2 Residual Strength Calculations

The output of the CFATIGUE routine did not calculate a residual strength after the fatigue analysis was completed. This is a necessary step; however, it was not regarded as an inherently easy task to implement. The residual strength of a joint incorporates the collection of multiple failure modes that might occur. These failure modes may or may not have an interaction with each other and they may or may not be allowed to progressively occur based on overall program requirements. Residual strength is often determined at an elevated temperature and moisture condition. Progressive damage finite element analysis at these conditions remains a gap that has not been addressed within the PDA community. The easiest implementation of a residual strength calculation is to utilize the cycle-by-cycle crack growth output from the CFATIGUE routine to get a picture of what the damaged area looks like on the structure, then perform the residual strength determination via traditional joint strength methods. Other automatic calculations of residual strength and their implementation need to be investigated but had not been at the writing of this paper.

3.3 FSLL Method Validation

The B-Basis allowables development work performed on ABCD Phase 3 detemermined a Mode III fracture toughness for the graphite/epoxy fabric material used here. The VCCT method used in the static and CFATIGUE analysis calculated the ratio of total strain energy at the crack tip to the combined equivalent critical strain energy. When that ratio exceeds unity, then the crack front is updated. The method of interacting the modal strain energies in the calculation of the combined equivalent critical strain energy needs to specifically account for Mode III fracture toughness data being generated. The previous method used the BK method to determine the combined equivalent critical strain energy, which is as follows:

$$G_{equiv-C} = G_{IC} + (G_{IIC} - G_{IC})\left(\frac{G_2 + G_3}{G_{total}}\right)^{\eta}$$

Where G_{IC} and G_{IIC} are the modal fracture toughness values for the material. G_2 and G_3 are the actual strain energies in the II and III shear directions for that load increment, and G_{total} sum of all three directional strain energies. η is a mode mixity value determined from testing. This method does not account for a unique Mode III fracture toughness value (G_{IIIC}) as this data is not typically available. It is assumed that the Mode II and Mode III fracture toughness values are equivalent. Within the ABAQUS VCCT static analysis, methods were already implemented which could capture the effects of a unique G_{IIIC} value. For example, the Reeder, or modified BK method [4] which is as follows:

$$G_{equiv-C} = G_{IC} + (G_{IIC} - G_{IC})\left(\frac{G_2 + G_3}{G_{total}}\right)^{\eta} + (G_{IIIC} - G_{IIC})\left(\frac{G_3}{G_2 + G_3}\right)\left(\frac{G_2 + G_3}{G_{total}}\right)^{\eta}$$

Here an additional term is added to the BK method that incorporates G_{IIIC}. Some additional work is needed to implement this method into the CFATIGUE interaction routine, however, the other theories already account for a G_{IIIC} value.

A sub-element fatigue test data is needed to generate applicable data to fully validate the interaction methods implemented in the CFATIGUE method for FSLL analysis. This is a planned activity for the Phase 3 B-Basis Allowables effort.

3.4 Mixed Mode Sub-Element Configuration Analysis

Several mixed mode specimen geometries were initially considered for the sub-element test. Specimen geometries included a bonded multi-stringer panel in a shear picture frame test fixture to a torque tube as used in the FAA report "Characterization of In-Plane, Shear-Loaded Adhesive Lap Joints: Experiments and Analysis" [5]. Due to perceived difficulties in test complexity and inspection, the torque tube configuration, seen in Figure 4-a, was selected. This test configuration had a square tube that was made up of three aluminum sides and a bonded specimen side, all of which were fastened together. The bonded specimen side would be altered from the original design to be a bonded composite design. The FAA report also indicated that two bonded side configurations were tested. One configuration used a joggled adherend to maintain the overall load line of the specimen. The other configuration did not utilize a joggle in the lower adherend, instead used a flat laminate and doublers. The assembled square tube was then inserted into a test fixture and an external torque was applied to the tube until the bonded specimen side failed.

An analysis model of the torque tube sub-element was built using shell elements for the three metal side walls and continuum shell elements for the joggled composite sub-element (Figure 4-b). A VCCT surface was defined between the two composite adherends in the joggled area and was assigned a Reeder Law mode mixing behavior with estimated fracture toughness properties. A torque was applied to one end of the specimen and the applied torque was reacted on the opposite side. The model was analyzed using the implicit solver in ABAQUS 2018, which included the recent method improvements to the VCCT solution.

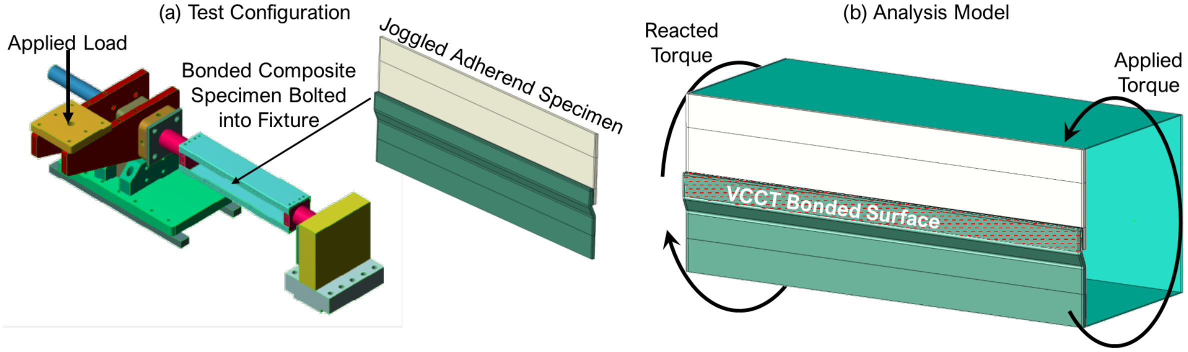


Figure 4: Torque Tube Sub-Element Configuration

The implicit analysis ran to a point where a significant amount of cracked area had developed, then failed to meet the convergence criteria of the static solution. The moment-rotation behavior of the torque tube sub-element and the final displaced shape can be seen in Figure 5. The model showed that the adherends of the joggled specimen buckle in a diagonal tension at a relatively low load compared to the peak load. It also showed that the onset of crack growth occurs near the peak load.

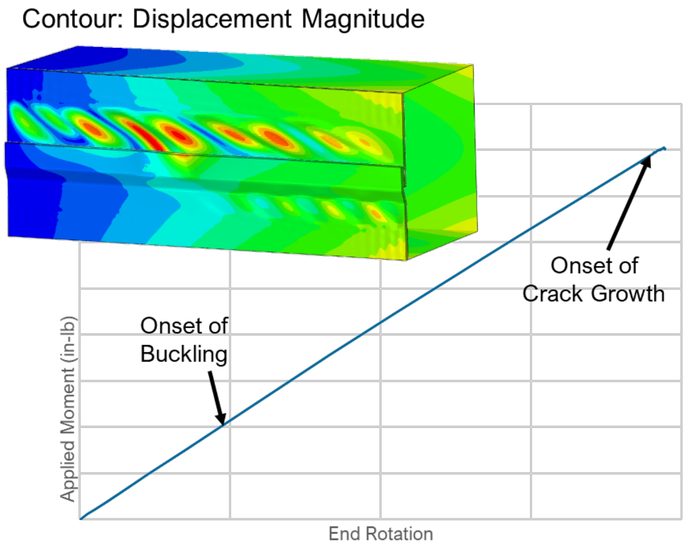


Figure 5: Torque Tube Sub-Element Displaced Shape and Load-Displacement Behavior

Figure 6 shows the bondline status of the VCCT surface during the analysis. In each successive image, the blue regions are bonded, and the red regions are disbonded. The location of crack initiation can be seen near the middle of the bondline length. This location correlates with a peeling location in the diagonal tension buckled pattern. As load is applied beyond this point, crack growth occurs from the initiation site.

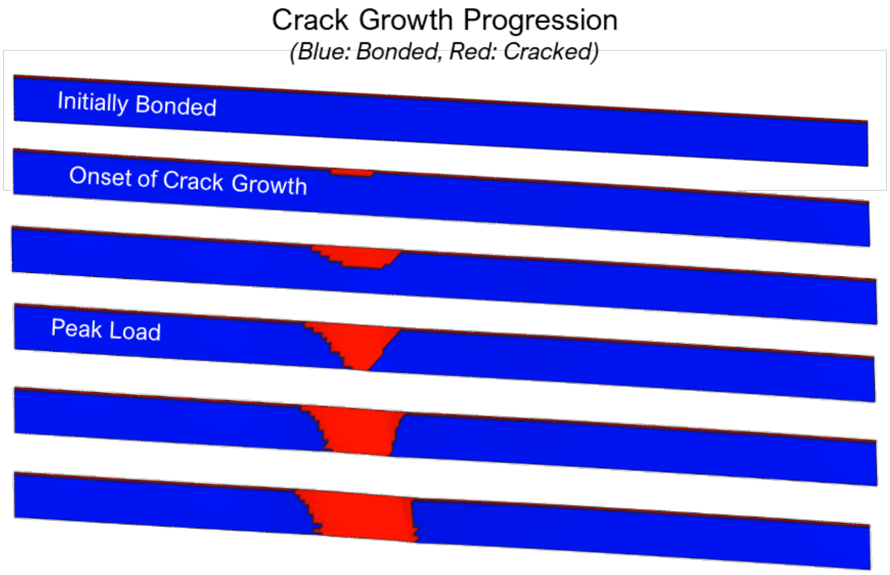


Figure 6: Torque Tube Sub-Element Crack Growth Solution

Figure 7 shows the strain energy distribution at the crack initiation location. The analysis showed that the crack initiated in a mixed mode manner. At initiation, the crack front showed a mixture of Mode I, Mode II, and Mode III strain energies. The model also showed how the strain energy builds up to initiation of crack growth. When the load was below the buckling load of the upper adherend, the all the strain energy at the crack tip was Mode III. After the buckling, the rate at which Mode III strain energy built up was significantly reduced while Modes I and II strain energy began to build up.

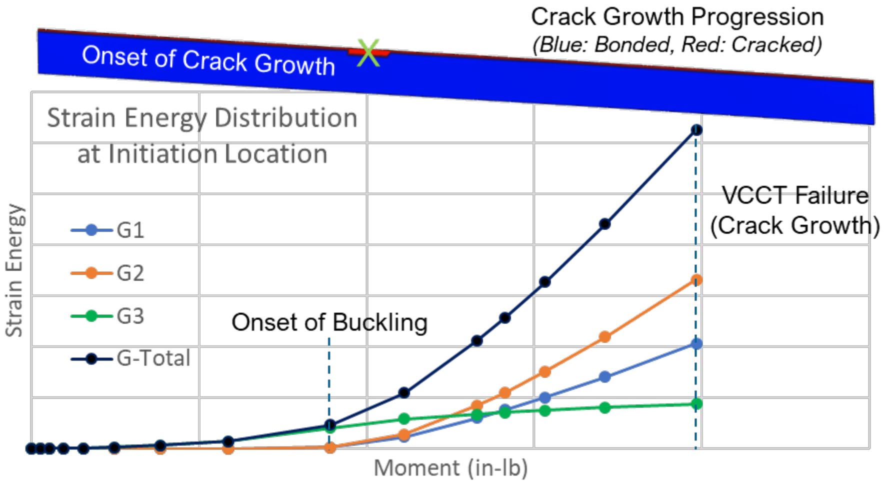


Figure 7: Torque Tube Sub-Element Strain Energy Distribution at Crack Initiation Location

The results of the torque tube sub-element analysis showed that a crack could grow in the bondline in a mixed mode manner. To achieve the mixed mode behavior, the bonded composite specimen would have to buckle, which would then produce the strain energies in the I and II directions. If the loading was not high enough to buckle the upper adherend, then only a Mode III crack growth would occur. The specifics of the test setup and data capture requirements were also discussed. It was concluded that the fixturing, setup, and inspection of the torque tube sub-element would be excessively cumbersome.

To simplify the sub-element design, the rail shear test apparatus from ASTM-D4255 [6] was investigated (Figure 8). This test configuration used a basic tensile setup with pinned load plates and rails connected to opposite sides of the specimen to generate a shear loading. The sub-element design was modified from the ASTM D4255 specimen to include a bonded lap shear joint between two adherends. One adherend was designed with a flat termination while the other adherend was designed with a ramped termination. This design aspect was intended to control which edge the crack growth would emerge from during the test and have a better correlation to joint configurations encountered in aircraft design. Doublers were added to the adherends at the rail connection edges to maintain a planar load path.

A finite element model of the rail shear sub-element was built using continuum shell elements (Figure 8). The bonded joint area was assigned VCCT contact properties that followed the Reeder Law mode mixing behavior with estimated fracture toughness properties. The doublers were also modeled and given the same VCCT contact properties to capture any crack growth that may occur. The implicit analysis was completed using ABAQUS 2018.

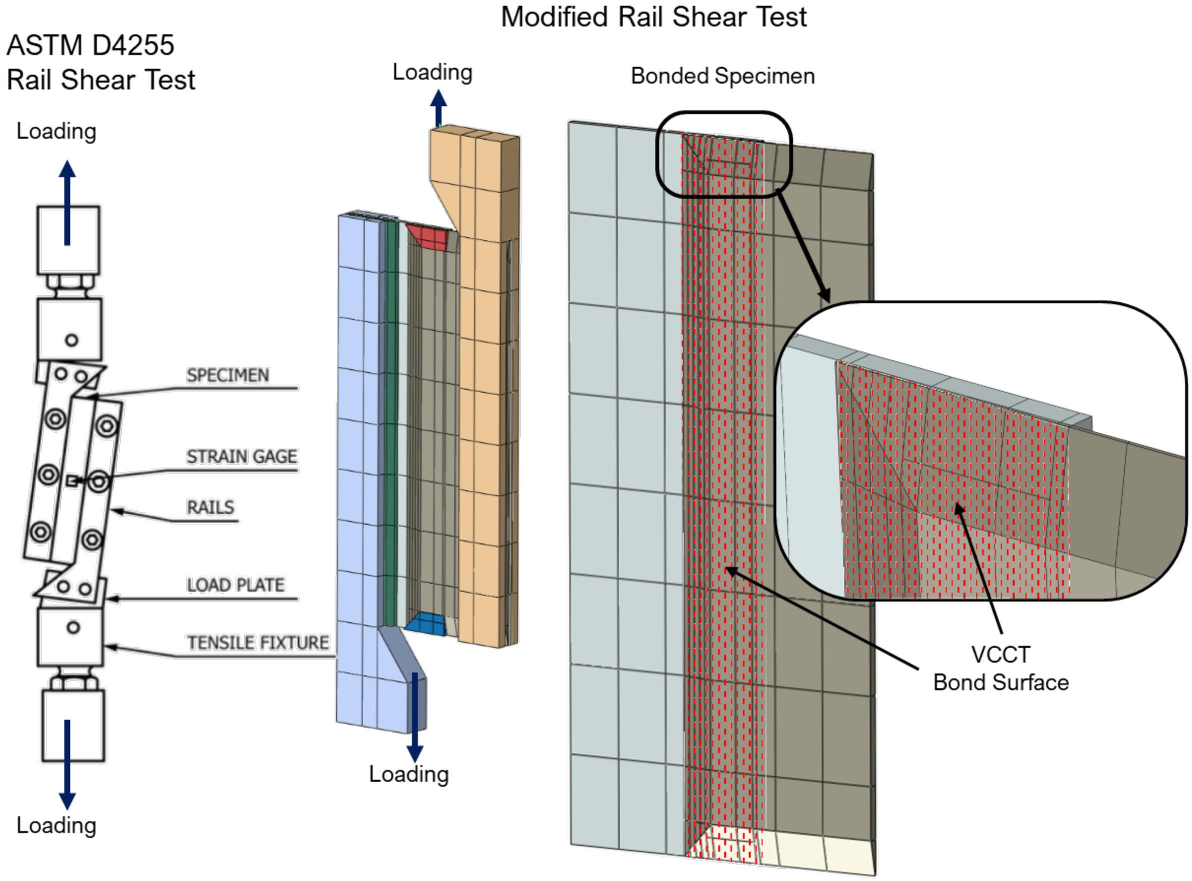


Figure 8: Rail Shear Sub-Element

The initial layout of the rail shear sub-element model used a constant cross-section for the full specimen length. Figure 9 shows the results obtained from the initial specimen layout. Overall, the specimen remained stable throughout the load application. Load was applied on the specimen up to the point where the crack growth solution began to grow. After a small amount of crack growth was achieved, the solution failed to meet the convergence criteria.

Figure 10 shows the VCCT solution for the lap shear and doubler bondlines. The analysis showed the crack initiated and grew from the free edge corners of the specimen and doublers. The crack growth under the doubler was a source of concern for this sub-element configuration. Follow on design modifications included a more generous ramp for the doubler edges and need to implement accurate fracture toughness properties for doubler to adherend bond, which may be different from the primary bondline in the specimen. Figure 11 shows the strain energy distribution calculated by the model at two locations of the specimen bondline. The first location is at the free edge corner of the specimen bondline where the crack initiated. The crack growth occurred in a mixed mode behavior with an even distribution of peel (Mode I) and shear modes (Mode II). While the goal of the sub-element was to generate fatigue mixed mode crack growth, the peel mode generated by the free effects seen here were not the intended behavior. The design of the specimen was modified to include a ramp on the upper and lower edge of the specimen and incorporate the effects of an end plate to reduce the peeling mode seen at the free edge. This is intended to move the crack initiation location towards the middle of the specimen where an even distribution of shear load is achieved. The second location shown in Figure 11 confirmed the expected shear dominated loading in the middle of the bondline. At this location, a mixture of Mode II and Mode III strain energy was calculated with no significant Mode I strain energy.

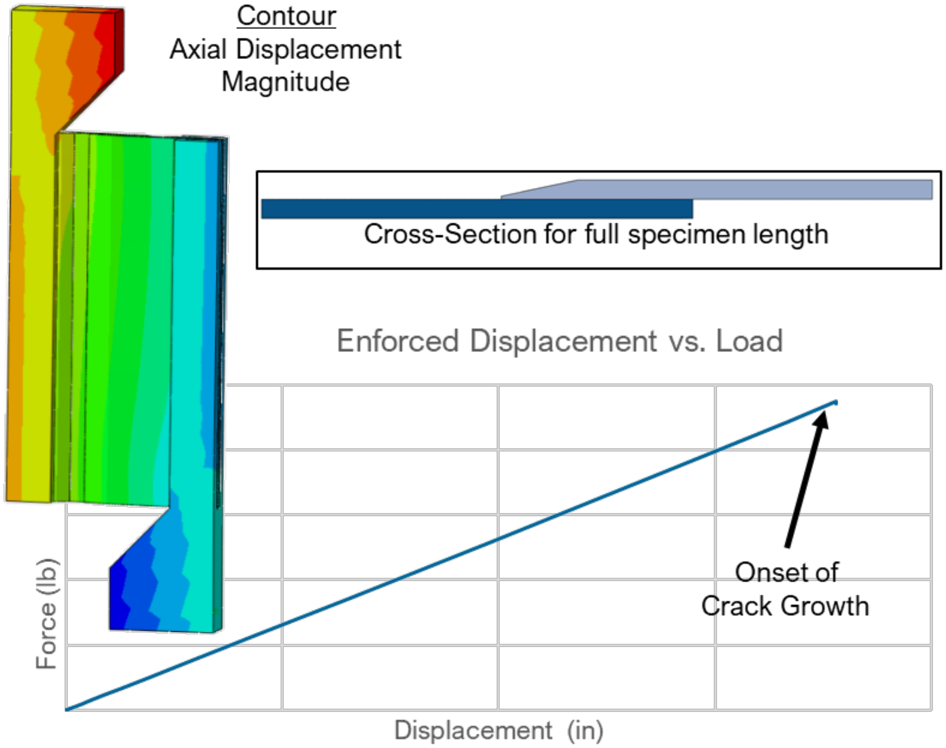


Figure 9: Rail Shear Sub-Element Global Results of Initial Layout

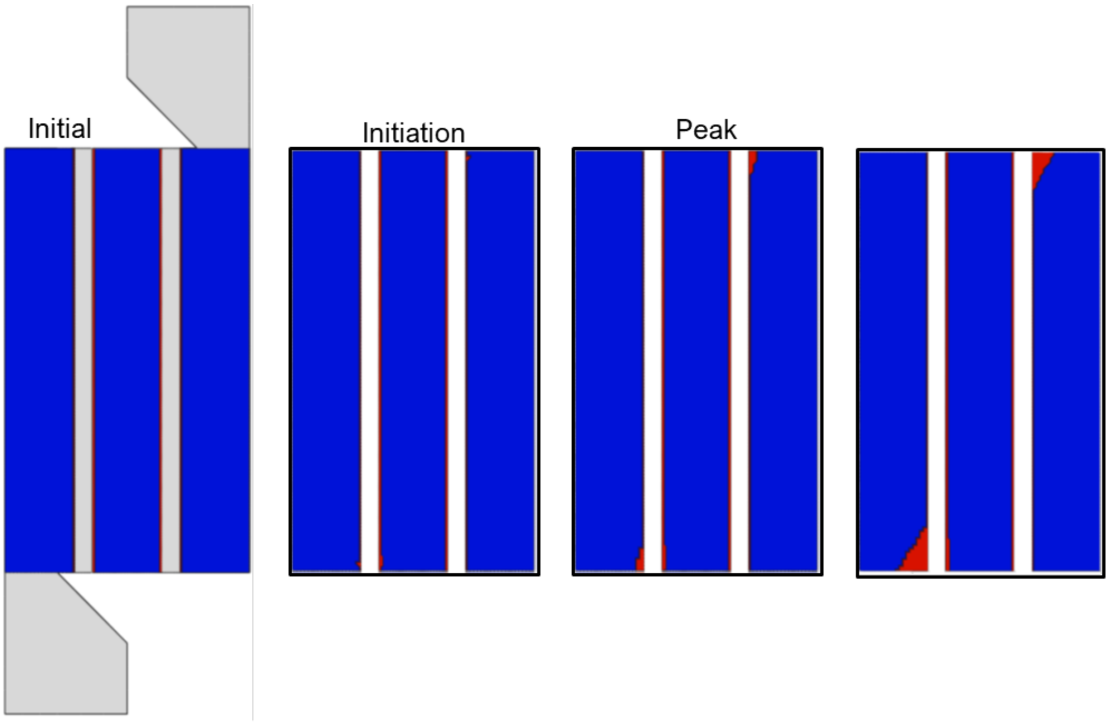


Figure 10: Rail Shear Sub-Element Crack Growth Solution of Initial Layout

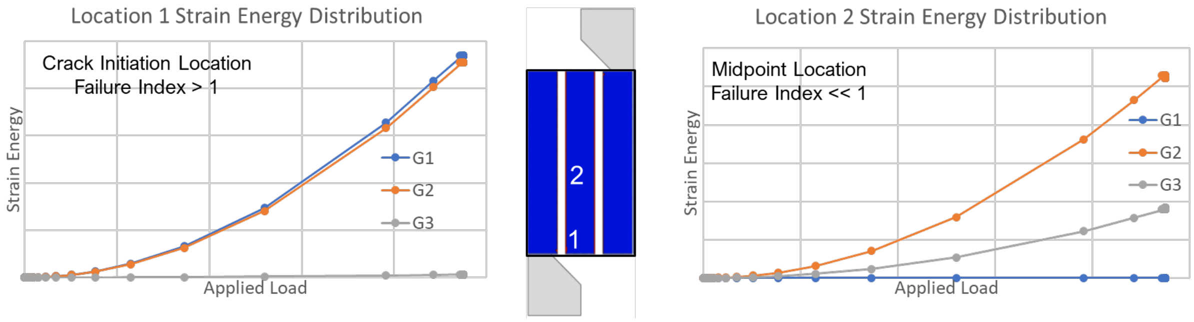


Figure 11: Rail Shear Sub-Element Strain Energy Distribution at Two Locations of Initial Layout

Overall, the rail shear sub-element configuration analysis showed the ability to generate a mixed mode strain energy distribution along the bonded joint. This is achieved through the whole loading range without requiring a post buckled behavior to generate the mixed mode crack growth. The necessary fixturing was also simplified which would also simplify the testing and inspection of the specimen.

4. CONCLUSIONS

Phase 3 of the ABCD program was tasked with addressing some of the phase 2 gaps in testing and analysis of bonded fabric composite parts subjected to fatigue cycling. It was determined that the interlaminar static and fatigue data of fabric composite materials were still not adequate at the end of phase 2, therefore a test matrix was developed to increase the quality of data obtained for all crack growth modes and advance the test method and data reduction of Mode III testing. The test matrix will yield more confidence in the obtained data and the methods used as well as the necessary static and fatigue interlaminar material properties required for FSLL analysis. Changes to the FSLL analysis process were investigated to ensure the high-quality data begin generated by the testing efforts were properly captured, specifically the implementation of a unique Mode III fracture toughness material property into the mixed-mode crack growth method. Other method gaps, such as the ability to determination of residual strength after some damage has occurred, are planned to be investigated during the phase 3 effort. A significant gap in the FSLL analysis method dealt with static and fatigue validation, specifically in mixed-mode crack growth. It was determined that the necessary test configuration and was not available to begin to address the validation concerns, so a sub-element bonded composite test specimen was designed. A few configurations were considered with a conclusion that a rail shear test of a lap shear bonded joint would be capable of developing the necessary mixed-mode data to be used in validating the FSLL analysis method.

5. REFERENCES

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