Boeing Technical Journal

Effective Durability and Damage Tolerance Training: New Methods for Modern Learners

Brandon D. Chapman

Abstract – **In the aeronautical industry, development of fundamental skills in durability and damage tolerance (DaDT) is critically important for most engineers engaged in structural design and analysis tasks. These skills are not usually well covered in most U.S. university undergraduate curricula, and individual coaching or on-the-job training are simply not efficient means of acquiring these skills at a basic level. An additional consideration is that the traditional classroom instruction formats are losing some of their effectiveness, as modern learners entering the workforce today have grown accustomed to a more hands-on style of learning. As a pilot program in transforming the Boeing Commercial Airplanes (BCA) Structures Engineering foundational training curricula, we recently rebuilt the introductory DaDT classes, originally developed nearly 20 years ago, to have a more learner-centric focus. The introductory DaDT syllabus covers the fundamentals of durability, fail-safety and damage tolerance, and how these principles are used at BCA. Boeing has thousands of engineers engaged in work that is pertinent to the structural integrity of our commercial airplanes. Many of these engineers go on to take more in-depth training in which they learn how to apply our proprietary DaDT methods. We have taken a new approach for this introductory course that embraces modern learning methods as a means to increase student engagement and learning and knowledge/skill retention. In this paper we provide an overview of this endeavor and we share our learning architecture model, the perceived benefits, testimonials from learners, and our plans for the future.**

Index Terms – **Damage Tolerance, Durability, Fail-Safety, Fatigue, Learning, Training.**

I. Introduction

One challenge that is easy to overlook in our industry is the ability to maintain skill continuity in the highly specialized (and sometimes subjective) technical disciplines surrounding structural integrity, beyond fundamental stress analysis and strength checks. Although U.S. Government projections indicate relatively low (less than 1 percent) annual employment growth rates in aerospace engineering over the next decade [1], the reality is that the industry is faced with significant turnover due to age demographics, globalization, shifting skill needs, and competition from other industries, at a time when commercial airplane demand is expected to surge. These are expected to become particularly acute issues in the fields of composite structures and stress engineering, which includes fatigue and damage tolerance.

BCA currently has more than 7,000 engineers who have access to the internal documents and tools that are used for durability (including fatigue and corrosion prevention) and damage tolerance (DaDT) design and analysis. The BCA methods for DaDT were developed such that they could be practically applied by program engineers with limited instructor-led training plus on-the-job training and coaching [2-4]. The idea was that most BCA engineers would be able to apply the methods without necessarily having to become subject matter experts in DaDT. However, having a workforce that possesses a deeper understanding of these topics is obviously desirable. This applies not only to the engineers directly involved in DaDT analysis, but also the larger population of engineers across many disciplines where DaDT plays a significant role in the safety and economics of the airframe, including design, loads, manufacturing, production, liaison, fleet support, systems engineering, and materials/process technology. An effective means by which to provide our entire engineering workforce with a foundational appreciation and understanding of DaDT is therefore vitally important to both the safety and economic (reliable) life of the airframe. It should be noted that while safety is of paramount importance, high reliability and low maintenance costs through proper design for DaDT are also critical for future product competitiveness.

Additional challenges BCA now faces include the high degree of dispersion of its engineering workforce (now across the U.S., Europe, Asia, and Australia) and the pressure to expedite the design cycle, which means bringing engineers into a state of acceptable proficiency in less time. Our workforce is furthermore considerably more culturally diverse. Our goal at Boeing is to create a more inclusive, practical learning environment so that all engineers can move to proficiency more quickly. The idea is to leverage the diversity inherent in our employee population and better transition the learning to on-the-job performance. In the past, the BCA Structures Engineering New Hire training featured lengthy, traditional instructor-led classroom lectures accompanied by printed copies of the projected slides. The introductory DaDT portion of this curriculum in particular consisted of a full-day in-classroom lecture. This covered the basic concepts while providing an overview of how BCA structures are designed and analyzed for DaDT. It is clear that this more traditional lecture approach tends to be a very passive experience for the students, as their feedback reflects. The effectiveness of this approach is also questionable when consideration is given to the large amount of information that is conveyed in a short time frame, which is certain likely to exceed the retention capacity of most learners. Moreover, we recognized that most New Hire (0-6 months) engineers will not necessarily have opportunities to immediately apply their learning on the job. If the students do not have the opportunity to immediately apply their learning, then the knowledge is less likely to stick.

The more traditional style of instruction is clearly less conducive to knowledge transfer. To this point, Carl Weiman, a Nobel Laureate and professor of physics at Stanford, has emphasized the need for student activity to enhance learning with the following comments in an interview [5]:

> *"You give people lectures, and [some students] go away and learn the stuff. But it wasn't that they learned it from lecture – they learned it from homework, from assignments. When we measure how little people learn from an actual lecture, it's just really small."* – Professor Carl Weiman

Today, modern learners entering our industry have grown accustomed to more effective means of teaching [6] and come from a wider range of life experiences. As a first step in an endeavor to transform this training series, we assembled a team of technical experts, working in collaboration with our internal learning development organization, Structures University, to improve the introductory DaDT course [7]. Recognizing that not all of our engineers will immediately encounter these concepts in their functions, we saw a heightened need to improve the effectiveness and knowledge retention of this training. The approach taken was to embrace modern learning methods. The new training, while still primarily instructor-focused, relies heavily upon team-based and problem-based learning, and by all indications, it is meeting its intended objectives.

II. LEARNING OBJECTIVES FOR INTRODUCTORY DADT

The new BCA structures introductory DaDT course is titled *Introduction to Durability and Damage Tolerance* (internal course number: SEU0120). The course aims to cover, in a single day, the fundamentals of durability, fail-safety and damage tolerance, and how these concepts are applied at BCA. Engineers who will engage in DaDT analysis will go on to take more advanced and in-depth training classes. Figure 1 shows the complete learning path for stress analysts in BCA who are engaged in DaDT analysis work. The classes that come after SEU0120 also include some aspects of problem-based learning. Those classes are targeted to stress analysis tasks and by necessity involve in-class problem solving. For instance, each of these courses now culminates in a post-class assessment problem that must be satisfactorily completed in order to receive credit for the training. These assessments or 'practicums' provide the students with opportunities to solve real-world problems to help solidify and verify their learning.

A much more significant transformation was needed for the introductory DaDT class. The new SEU0120 course is focused on providing those engineers embarking on the learning path shown in Figure 1, along with the larger workforce in other disciplines, a foundational understanding of DaDT. The reality is that most of our Structures Engineers who come to Boeing after graduating with an undergraduate degree in Mechanical, Aerospace, or Civil Engineering (particularly in the U.S.) are unlikely to have covered fatigue or fracture mechanics at any significant length as part of their education. Topics in fatigue, at most U.S. universities and colleges, will tend to limit applications to safe-life design approaches (i.e., endurance limits) that are not practical for most of our airframe structures. When it comes to damage tolerance, most classes on the topic of fracture mechanics tend to be offered as senior-level elective courses or at the graduate level.

We began the development of the SEU0120 course by re-evaluating the learning objectives. Instead of starting with vague objectives (e.g., "in this class the student will develop an understanding of fatigue") we sought to define measureable objectives that were deliberately written in terms of things that the students can do and then be immediately assessed upon. In other words, we developed learning objectives that were actionable and measurable. Another important aspect of re-evaluating the learning objectives was that we were able to align those objectives to better match the core competencies that are now defined for both the design and stress skill codes. These design and stress competencies describe the foundation of what the structures engineer does and how he or she does it, emphasizing engineering fundamentals, but also addressing more advanced competencies as well.

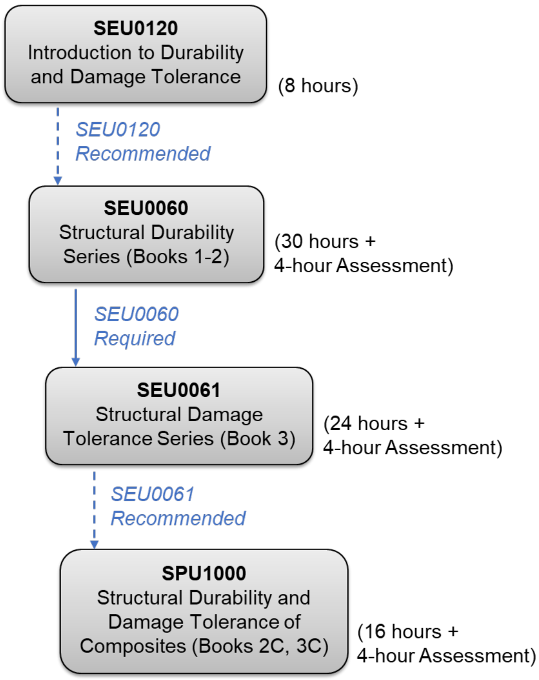

Figure 1. Typical learning path for stress analysts engaged in durability and damage tolerance analysis for Boeing Commercial Airplanes.

We identified over 30 learning objectives for the new SEU0120 class. These are written in the form of questions and provided to the students ahead of the workshop so that they can help track their progress through the course and, later, after the in-class instruction is over. A few specific examples of the learning objectives include—

1. *What are common sources where fatigue damage might originate in metallic structure? Describe the mechanism of each using specific examples.*
2. *What are the three damage management strategies of safe-life, fail-safety and damage tolerance? What are the advantages and disadvantages of each?*
3. *Explain the concept of the stress intensity factor. What are the most important uses of this parameter?*
4. *What are common in-service, non-destructive inspection (NDI) methods and how are they typically used?*
5. *How are damage tolerance supplemental inspection program and baseline inspections developed and implemented? What are the fundamental roles Boeing, regulators, and operators play in this process?*
6. *What are the concepts of Visible Impact Damage (VID) and Barely Visible Impact Damage (BVID) in composites? How can they influence the sizing of large notch composite structures?*
7. *Why is designing for accessibility, inspectability and repairability important? How do these factors impact DaDT?*

The next step was to determine the optimal instructional tools and techniques to best meet those objectives. We strived to follow the guidelines set forth long ago in Bloom's taxonomy of learning [8], which rank skills from simple memorization and understanding of factual information to higher-level skills that involve reasoning and problem-solving. For application to our introductory class, we identified our target skill levels on a more simplified three-level scale: (1) *knowledge*, where the student can name and identify factual information, (2) *skill*, where the student can apply that knowledge at a basic level, and (3) *ability*, where the student can demonstrate higher-level or critical thinking.

We then went through each learning objective and identified the target skill level and then identified the appropriate instructional tools and media to help the students meet that particular objective. For example, an objective of being able to identify the differences between ultimate, limit and operational loads was deemed to be a knowledge level. It was then determined that instructor-led lecture using examples and videos was the appropriate media to achieve that particular learning objective. On the other hand, an objective that the students be able to contrast and compare the strategies of safe-life, fail-safety and damage tolerance was deemed to be a skill level. In this case, it was determined that instructor-led lecture should be augmented by a team-based learning activity followed by in-class discussion. This exercise during the early stages of course development proved to be very helpful because it established the blueprints and laid out the path for success.

The desire to have students frequently and closely interact among themselves and with the instructor during the training meant that, unlike the more traditional classroom format, this type of introductory workshop has some definite class size limits (15 to 20 students being the ideal range, by our reckoning) and a more intensive level of involvement by the instructor. We felt, however, that this was a price worth paying, given the net value of the experience for the students. Additionally, we found ways to mitigate some of these constraints by encouraging more of our experienced, promising early- or mid-career engineers to participate in the workshops as instructor assistants, with the obvious benefit that these individuals can now gain the confidence and experience they need to become future instructors themselves, as well as give them the opportunity to connect with, and be known to their new peers.

III. INDUCTIVE LEARNING APPROACHES

The new class primarily takes advantage of two effective learning techniques: inductive learning and active learning. The first of these techniques, inductive learning (a.k.a., "backwards teaching"), is inquiry-based, problem-based learning (Figure 2) [9]. The students are initially challenged with questions, observations, or data that they themselves must use to define the problem and the needs. The instructor can then provide several discrete lessons that gradually introduce the students to the underlying theory, principles and methods. But finding the solution to the problem at hand is now primarily a learner-centered activity, involving iterative loops as the students incrementally gain the necessary tools, allowing them to refine their initial thinking or solution.

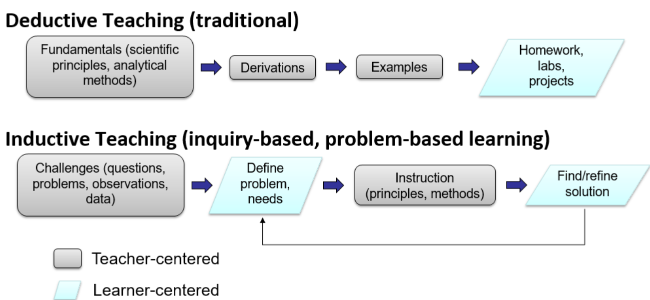

Figure 2. Deductive and inductive teaching models [adapted from Reference 9].

While inductive learning may seem to be an obvious choice—engineers, by their nature, are already great problem solvers—this approach is not used as frequently as it could (or should) be when it comes to our required technical training. Most of our instructors are subject matter experts in their field, which makes it rather natural to take an approach to teaching that relies more upon traditional lecturing (i.e., teacher-centered). In other words, the past thinking has been that if you want to teach DaDT, then bring in a recognized expert to 'lecture' the students on the subject. The effectiveness of this teaching model was probably further reduced because the training syllabus and work schedule demands did not allow time for learner-centered activities such as homework, labs or projects.

Our foundational class (or workshop, as we prefer to call it) begins with a challenge to look at a notable fatigue cracking event in service – namely, a real event in which a Boeing 737-300 experienced an accidental in-flight decompression event (Figure 3). This exposes the students to real-world problems related to DaDT. We provide each team of students with a large laminated sheet containing photographs of the damaged structure. We ask the students to imagine that they are part of the National Transportation Safety Board (NTSB) team of investigators arriving on the scene and looking at the evidence to determine what led to this event. We also ask them to identify features of how the structure was designed such that catastrophic failure did not occur (i.e., fail-safety worked). While they are not likely to come up with all of the answers, they will at least begin to recognize the issues and problems. In this case, it is a backwards way of teaching the students concepts like stress concentration, secondary bending in certain types of joints, and fail-safety, in a very visceral way. Even though most of the students will not know what a "chem-mill step" in a fuselage skin is at this stage in their training, in less than 10 minutes, most students, working as teams with instructor guidance, are able to quickly dissect the problem. One significant advantage of this approach is that it gives the students an immediate and tangible sense of purpose for being in the workshop. Now that they are intimately involved with the challenge, and now that they appreciate why they are in the class, they are better motivated and ready to learn the fundamentals of fatigue, fail-safety, and damage tolerance.

Figure 3. Example of an in-service structural failure used for an inductive learning approach to fatigue cracking and the merits of fail-safe design [10].

As the class progresses, the students are incrementally exposed to the theory and tools that they can utilize to further their understanding of this in-service decompression event. For example, the students soon learn about static versus fatigue-induced fracture morphologies. They learn how stress concentrations and load eccentricity relate to fatigue cracking. They are exposed to numerous examples and case studies of fatigue cracking in aircraft structures (Figure 4). It is not until near the end of the class when we actually reveal the primary cause of the accident depicted in Figure 3 (in this case, the pillowing effect in the fuselage skin near non-chem-milled, stiffer areas of the skins located in the vicinity of pockets). In this manner, the learning becomes more of a journey of discovery; the newly acquired knowledge is more likely to be retained and the student understands how what they will do and the decisions they will make in the course of their work can have a real impact on the integrity of the structure.

This idea of backwards teaching (or "flipped classroom") is utilized throughout the course whenever possible. For instance, when introducing the concept of stress concentration and fatigue cracking, instead of immediately showing the students examples of where cracking can occur, we first challenge them to come up with a list of examples of fatigue cracking mechanisms. Most students already have a good idea of stress concentrations and where cracking can occur. By working in teams with instructor guidance, we help them arrive at a more comprehensive list. This activity is helped by instructors (typically the principal instructor and his/her class assistants) moving about the classroom and working with the various teams, asking thought-provoking questions. The idea is to help facilitate deeper learning by prompting the students with more questions (a.k.a., the Socratic method of teaching). For example, the instructor might join a group of students and say:

- "*You have identified several good examples of stress concentrations caused by removing material from the structure, but what if we add material to the structure? Can that also lead to stress concentration?*"

- *"What if we change how or where the structure is loaded? Do you think that will affect the stress concentration? If so, how?"*

Questions like this can open up new avenues where a range of ideas and concepts can be explored.

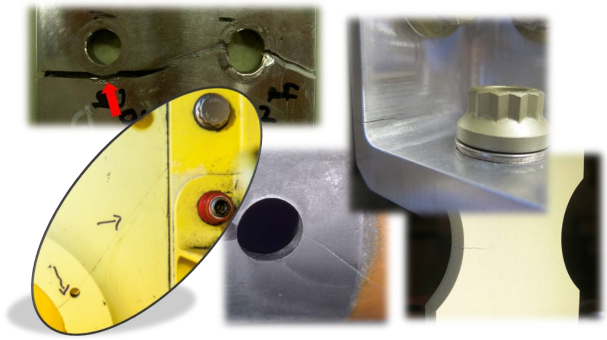

Figure 4. Photo collage of examples of fatigue cracking in metal aircraft structures that the students are exposed to in the classroom.

One final example backwards teaching that we have utilized to great effect has to do with the concept of the stress intensity factor in classical linear elastic fracture mechanics. Many textbooks on this subject begin with a derivation of stress field solutions for a Mode I crack in an infinite plate subject to tension. For instance, the Westergaard stress function involves writing the Airy stress function in terms of real and imaginary parts [11]. The drawback of this teaching model is that the students can get lost in the mathematics and underlying theory, without ever appreciating the actual utility of the stress intensity factor. Similarly, energy-based approaches to fracture mechanics favored in most textbooks on the subject, while elegant, tend to be too abstract for many students.

On the other hand, a backwards teaching model is achieved if one takes a more historical approach to the development of linear elastic fracture mechanics. For example, we begin coverage of this subject in the workshop with a conceptual approach that builds upon earlier discussions on the subject of stress concentrations. The approach recalls the original Inglis solutions for the stress concentration factor of elliptical holes in flat plates [12]. Using simple finite element models, we illustrate how classical stress analysis predicts infinite stresses in the vicinity of a crack tip (Figure 5). The students quickly discover the deficiency of such an approach and thus recognize the need for linear elastic fracture mechanics as an engineering tool. This sets the stage for introducing the students to the stress intensity factor, which of course provides a means of measuring the intensity of the stress field in the vicinity of a crack tip. We then proceed to show the students how this new parameter can be used to quantify both the residual strength and crack growth in cracked structures, which are key pillars in damage tolerance analysis.

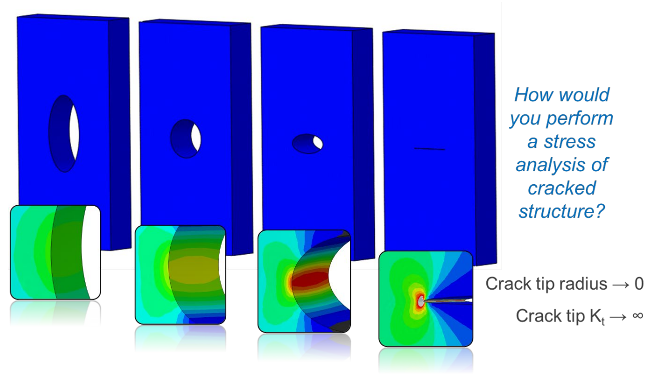

Figure 5. Example of a conceptual learning approach to introducing students to linear elastic fracture mechanics.

IV. ACTIVE LEARNING APPROACHES

The second technique that we utilize in this class involves the concept of active learning. At the most basic level, active learning is anything students do in class to learn material, other than listen to the instructor and take notes [9]. The key elements are activity and engagement. Learning that is hands-on and experiential tends to be more effective because the learner can do something and get immediate feedback. It is important to recognize that active learning is a spectrum (Figure 6). The class can still be primarily instructor-focused on the active learning continuum. Active learning can be as simple as stopping the lecture periodically and giving the students an opportunity write down key learnings or notes about concepts where they might still lack clarity. These writings are then invited to be shared with neighbors, or the entire class for instructor-led class discussions (a.k.a. "think-pair-share"). We have used this to great effect in our class, by never lecturing for more than 30 minutes continuously without stopping for individual reflections and class discussions. One good test of whether the student is learning is to see if they can turn around and explain these concepts to others in their own words. This approach is also enormously valuable because it affords the instructor immediate feedback regarding the effectiveness of the presented material. By directly engaging with the class, the instructor is able to find out what the students are (or are not) comprehending.

Related to this, we have more recently been able to take advantage of the new Poll Everywhere tool. This tool, which is readily available in Boeing Software Express as an add-on to PowerPoint, provides tremendous flexibility in terms of conducting in-class polls. Instead of asking the students to shout out their responses (which invariably only engages a subset of the class), the tool allows all students to submit their responses anonymously, using either their personal phones or a computer. The tool can be used to see in real-time where the students are at in terms of their understanding or interpretation of the materials, at any given point in the course.

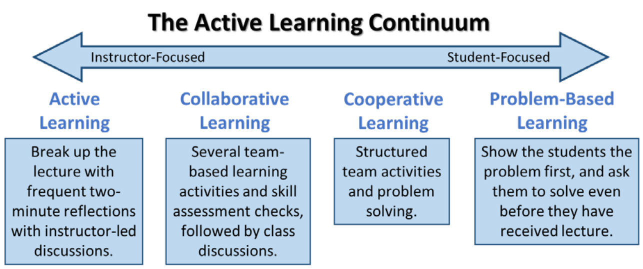

Figure 6. The active learning continuum [adapted from Reference 9].

The class also employs active learning by incorporating several structured team-based activities for collaborative and cooperative learning (i.e., the central part of the learning continuum depicted in Figure 6). For example, we have several short learning assessments that the students complete in class. A good question raised during class can provoke curiosity, stimulate thought, illustrate the true meaning of lecture material, and trigger a discussion or some other form of student activity that leads to new or deeper understanding. These periodic "pop quizzes" are not turned in. Instead, we encourage to students to discuss their responses with their fellow classmates. This again allows the students to try to express the material in their own words, and to apply it to real problems or questions. This moreover creates a means for the instructor to obtain immediate feedback, either by walking around the room and listening to the students, or by directly joining their discussions. These learning assessment problems provide opportunities to ensure that the students are grasping the concepts before moving on to a new topic. These are also great examples of both collaborative and cooperative learning.

In one illustrative example, after introducing the students to the basic concepts used in residual strength analysis, like stress intensity factor, fracture toughness, limit load, and net-section yield criteria, we then quickly dive into some hands-on tutorials. We utilize a simple Microsoft Excel®-based tool that allows the students to perform rudimentary residual strength analyses of center-cracked panels (Figure 7a). With this tool in hand, they quickly get a feel for the residual strength sensitivity to variables such as material properties and panel geometry. Moreover, this is a great means of providing the students a more hands-on feel for the utility of the stress intensity factor, which was introduced as a concept earlier in the workshop. A typical exercise is to give the students material properties for typical 2000- and 7000-series aluminum alloys, and then determine the critical crack sizes for various residual strength requirements. Based on this rudimentary analysis, we can then expect the students to use critical thinking to determine which material would be the better choice for fracture- or fatigue-critical areas of the structure, for instance, in upper and lower wing skin panels.

Similarly, in the case of fatigue crack growth, we guide the students through a problem that gives them a sense of common numerical results (Figure 7b). In this instance, we emphasize that the stress intensity factor is now used in conjunction with the operational stresses as the parameters controlling crack growth. We have found that this is a common conceptual challenge for the students – namely, in understanding the influence of cycles and cyclic operational stresses, as opposed to dealing with a discrete stress of a set magnitude, as in a residual strength evaluation. We ask them questions such as what happens to the overall cycles-to-critical if the minimum detectable crack length can be reduced. This way, they learn, by direct experience rather than by the instructor's word, that for this structural example, most of the crack growth life is in short cracks. The students are also asked to analyze crack growth under different operational stresses, which is a simple exercise that gives them a feel for the sensitivity of window of detectability on the applied stresses.

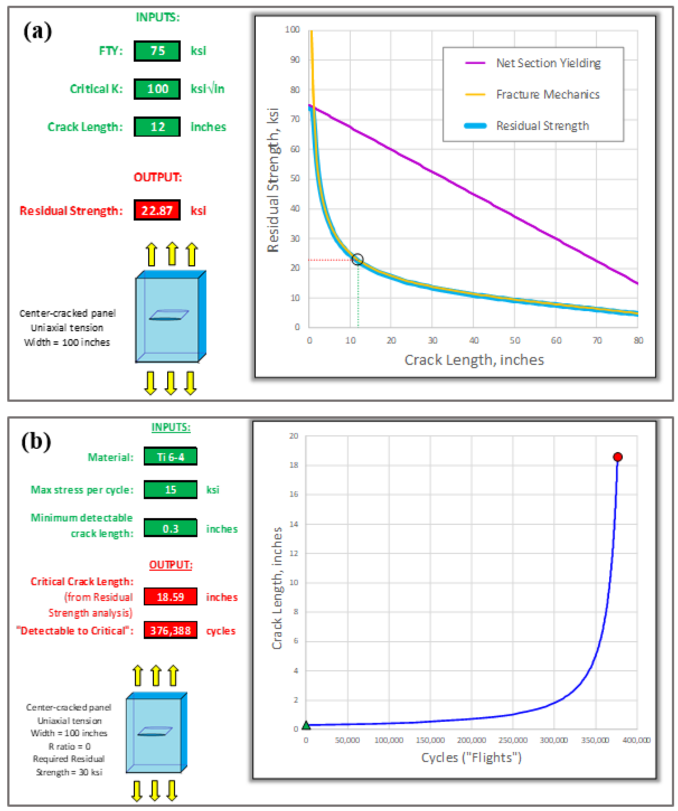

Figure 7. Examples of simple spreadsheet tools developed to allow students to execute the most rudimentary damage tolerance analysis of a center-cracked panel: **(a)** net section yield and fracture mechanics residual strength checks, **(b)** crack growth calculations.

V. THE VALUE OF REAL-LIFE EXPERIENTIAL LEARNING

Real-world cases studies can be a valuable learning tool. We work in a field where (unfortunately) in-service incidents and lessons learned from any number of causes are not entirely lacking. We take advantage of this by continually invoking and examining case studies throughout the workshop. Near the end of the training, we again "flip the classroom" by asking the students to perform investigations of some notable accidents attributed to loss of structural integrity that have occurred in recent aviation history (Figure 8). The students break into teams and utilize the FAA Lessons Learned website (https://lessonslearned.faa.gov), which we have found to be a great repository of information about significant events that have helped shape current aviation safety policies. Each team of students must first quickly familiarize themselves with one particularly key event – e.g., the de Havilland Comet 1 (1953-1954), Dan Air Boeing 707 (1977), JAL Boeing 747 (1985), Aloha Airlines Boeing 737 (1988), or China Airlines Boeing 747 (2002). We ask them to go online to do that or, if online access is not practical or possible, work from printed materials.

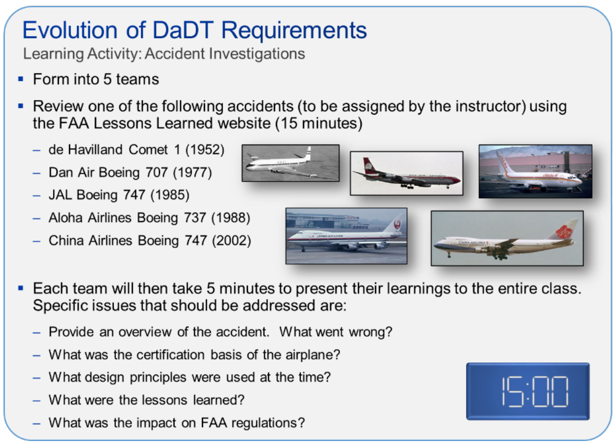

Figure 8. In-class activity to engage the students in commercial aircraft accident investigations.

During this in-class activity, the teams work together to answer several pertinent questions about these milestone events. *What went wrong? What design and certification principles were used at the time? What were the lessons learned? What was the impact to aviation regulatory requirements from these events?* Each team is then asked to summarize their findings in the form of a short presentation to the entire class. When we come to this point in the workshop, the instructors have already helped foster an environment where the students feel comfortable speaking openly about events that they may only know superficially. The students literally become the teachers at point. Aside from the obvious benefit of directly engaging the students, this activity has the additional benefit of (hopefully) getting a new generation of engineers excited about studying the past, because lessons learned from the past help us build a safer future. This approach additionally helps the student see the rules and regulations under which we operate as a rational evolution.

It should also be mentioned that all of the in-class activities and tutorials are contained within a printed workbook, which the students are individually issued at the start of the workshop and on which they are able to add notes and take with them after the class. The hope is that the students will expand their learning after leaving the classroom. We also provide the students with access to an internal Boeing website that is replete with DaDT resources, which they can access both prior to and after taking the class.

The development of this new introductory DaDT course was also initiated in the context of a broader effort within BCA Structures Engineering to shift the paradigm of training to one that instead focuses on student learning. The idea is to take a more holistic approach as we move from traditional to modern evidence based instructional practices. In the more traditional approach, training is directed, standardized, extensive (many hours of lecture), and tends to be a passive experience for the learner. Today, modern learners want answers right away and they rely on a wide variety of sources to find the answer. The means of delivery must be accessible, self-directed, current, and chunked (broken down into bite-size pieces). To facilitate this, we strive to deliver learning across a continuum, rather than just in the classroom. The goal is to move away from the typical "one-and-done" training approach. Instead of having our engineering workforce wait until they can get into a classroom, we seek to provide them with the means to pursue self-directed learning.

A further creative illustration of the commitment to education and training within BCA was the acquisition by Boeing of a retired 737-300 Classic (L/N 1231) fuselage (Figure 9) [13]. This airplane had accumulated over 73,000 flights over its 25-year service life and was destined for salvage and reclamation. Now it is used as a live training exhibit for structural engineers in the Puget Sound region. Since acquiring the retired fuselage in late 2012, over 3,200 Boeing engineers have visited the hull. Although not procured specifically for the SEU0120 class, we try to take advantage of this opportunity by encouraging all of our students in the Puget Sound area to take a tour of a retired 737 fuselage immediately after taking our course. The best DaDT teaching aid is to allow our engineers to explore a retired airframe and see first-hand structural modifications and repairs that tend to occur in the aging fleet.

Figure 9. Retired Boeing 737 fuselage training aid (Washington Design Center, Seattle).

Similarly, in 2014 the Boeing site at Seal Beach, California (home to the majority of our Fleet Services operations), acquired a retired 737-300 Classic airplane (L/N 1798), including fuselage, wing and empennage (Figure 10). This airplane began passenger service in 1989 and accumulated 38,678 flights and 55,603 flight hours prior to retirement. This display is regularly used as a training mechanism for early-career engineers. Most notably, the Customer Support Service Engineering Single Aisle

Airframe Engineering team, with the assistance of the Boeing Aircraft on Ground (AOG) team, leads an annual hands-on training class where engineers are afforded the opportunity to install structural repairs on the airframe [14]. To date, the AOG team has guided Customer Support engineers in performing more than twenty major repairs. This hands-on training has involved both Airframe Engineering teams seeking to gain real-world experience with routine customer in-service repairs, as well as Maintenance Engineering teams focused on repairs and tasks from Structure Repair Manuals and Service Bulletins. More recently, the Seal Beach site has expanded its collection to include a 787 Section 41, a 737 NG Door Demonstrator and sections of a 777-9 wing practice box. These additional components (not pictured here) will be used to further diversify the educational value of this unique "classroom." Considering there is no production facility in Seal Beach, these displays provide a unique opportunity for the engineering teams to see and experience our airplanes first-hand.

Figure 10. Retired Boeing 737 fuselage training aid (Southern California Design Center, Seal Beach).

Additionally, various teams have built smaller airplane structural displays that can be rolled into our classrooms in Everett and Kyiv or used as self-guided learning aids on permanent display. For instance, a window belt section from a retired 737-500 Classic (L/N 2614) is currently on display in the Everett 40-88 building, located adjacent to the Structures University classroom (Figure 11). Finally, DaDT test specimen kits were created and distributed to the other Boeing sites, thereby allowing our entire team of instructors across the enterprise to take full advantage of these important visual and tactile teaching aids.

Figure 11. 737 window belt display located in Boeing Everett (courtesy of William Browning).

VI. Closing Thoughts

The updated introductory DaDT workshop (SEU0120) was first offered to Boeing Structures Engineers at the Everett site in October 2016. Structures University has produced a short video highlighting the initial deployment of the workshop [15]. We have since been able to deploy this workshop at several Boeing sites that includes Everett, Renton, Seal Beach, and Charleston in the U.S., as well as at the Boeing Design Centers in Moscow, Russia; Kyiv, Ukraine; and in Melbourne, Australia. For delivery outside of the Puget Sound, we have relied upon local subject matter experts at the various Boeing sites to teach the class, after an orientation process by which we prepare and qualify them as instructors.

By invoking modern methods of teaching, we believe that we have been able to develop an introductory DaDT workshop that enhances student learning and knowledge retention at a foundational level. Unfortunately, we currently lack the resources to pursue in-depth post-training assessments, which would have been useful to accurately assess the effectiveness of the training. However, by striving to stay consistent with evidence-based means of effective training used in other disciplines, we have confidence that the changes in the course structure and delivery will have a lasting impact. The student feedback, which has been collected and analyzed using MetricsThatMatter® tools, does support this expectation. The responses from the students after taking this training has been overwhelmingly positive. Typical learner comments follow—

- *"I enjoyed the format of this class, specifically the increased focus on participation compared to other courses that I've taken thus far."*
- *"For me this is one of the best training classes I have attended at Boeing. I like the format, the instructor's energy and knowledge of the subject presented and enjoyed the dynamic interactions and activities."*
- *"I liked that in addition to the theory, we got to participate, do some problems and use case studies as examples of where we have seen the different types of phenomena in the past."*
- *"Doing the exercises as a group and having the instructors walk around to help guide the discussions was very beneficial. Also, having a website where the course content could be accessed before and after the class was very helpful."*

It has been said that the best teachers create an environment where students can try, fail and receive feedback, all without fear of embarrassment or ridicule. This idea is apparent in how we have structured our training. Our goal is to create an environment where the students can be active, engaged, make attempts to apply their learning, struggle with the material, possibly even make mistakes, and receive immediate feedback from their peers or the instructor. At the same time, we have strived to make the material 'fun' and visceral.

We continue to see this course enrich not just our DaDT analysts, but also engineers across many disciplines where DaDT plays a significant role in the safety and economics of the airframe, including design, loads, manufacturing, production, liaison, fleet support, systems engineering, and materials/process technology. Although we originally developed the DaDT training for the subset of stress analysts and design engineers engaged in DaDT work, we are finding that it has broader applicability to and value for a larger population of Boeing engineers. More recently, Liaison Engineering teams in Everett and Renton have added SEU0120 to their required core training curriculum. We have also deployed a variant of this class through the Ed Wells program, reaching approximately 110 SPEEA engineers from various engineering functions in six classes held from 2017 to 2019.

The work described here is of course not unique to DaDT training. Parallel efforts are underway at Boeing to transform other training curricula as well. Some of these efforts will look similar to what is described here. SDT has recently begun working with Structures University and a larger team of technical experts across BCA to develop a new course that will build upon SEU0120, with shifted emphasis to more functional learning in DaDT for all skill codes, not just those engineers who will go on to take the more advanced courses shown in Figure 1. Other developments are looking further ahead and how new technologies can help transform our training methods, all in an effort to improve the learner experience.

VII. Acknowledgment

The author would like to acknowledge the invaluable contributions by the following individuals who helped develop and deploy this training: Patricia Henderson, Bernardo Malfitano, Robert Jochum, Zachary Whitman, Austin Lee, Matthew Miller, Kazbek Karayev, Kenneth Dang, Frank Andrews, Jeffrey Sermersheim, Alan Stemple, Olga Sevostianova, Anton Kotelnikov, Ryan Schwartz, Jim Bates, Tayler Wiley and Monique Lundgren. The author would additionally like to thank Andrew Casale and William Browning for their contributions to this paper. Above all, the author would like to thank Antonio Rufin for his unwavering mentorship over the years, on this endeavor and many others.

VIII. References

[1] U.S. GAO Report (2014). *Aviation Workforce: Current and Future Availability of Aviation Engineering and Maintenance Professionals*, United States Government Accountability Office Report GAO-14-237 (external link).

[2] U. G. Goranson (1993). "Damage Tolerance Facts and Fiction," *14th Plantema Memorial Lecture, In: Proceedings of the 17th ICAF Symposium (Stockholm, Sweden)*, Volume I, pp. 3–105, A. F. Blom (Ed.), Engineering Materials Advisory Services Ltd., Warley, United Kingdom.

[3] S. A. Chisholm, A. C. Rufin, B. D. Chapman, and Q. J. Benson (2015). "Structural Durability and Damage Tolerance in the Next Century of Commercial Aviation," In: *Proceedings of the 28th ICAF Symposium (Helsinki, Finland)*, A. Siljander (Ed.).

[4] S. A. Chisholm, A. C. Rufin, B. D. Chapman, and Q. J. Benson (2016). "Forty Years of Structural Durability and Damage Tolerance at Boeing Commercial Airplanes," *Boeing Technical Journal*, Volume 6, Issue 3, Article No. 1 (2016).

[5] E. Westervelt (2016). *A Nobel Laureate's Education Plea: Revolutionize Teaching* (external link).

[6] R. C. Clark (2015). *Evidence-Based Training Methods: A Guide for Training Professionals*, 2nd Edition, ATD Press.

[7] A. C. Rufin (2017). "Design for an Inclusive Learning Environment at Boeing Structures Engineering University," American Society for Engineering Education (ASEE), Pacific Northwest Section Conference, Presentation, April 6-8, 2017, Seattle, Washington.

[8] B. S. Bloom (1956). *Taxonomy of Educational Objectives: The Classification of Educational Goals*. New York, NY, Longmans, Green.

[9] M. Prince, (2004). "Does Active Learning Work? A Review of the Research," *Journal of Engineering Education*, 93(3), 223-231, 2004.

[10] National Transportation Safety Board, NTSB (2009). Southwest Airlines Flight 2294, Factual Report No. 09-060 (ID No. DCA09FA065), September 3, 2009.

[11] D. Broek (1986). *Elementary Engineering Fracture Mechanics*, 4th Edition, Kluwer Academic Publishers.

[12] C. E. Inglis (1913). "Stresses in a Plate Due to the Presence of Cracks and Sharp Corners," Fifty-fourth Session of the Institution of Naval Architects, March 14, 1913.

[13] D. M. Lemke (2013), "Lessons Learned from a 737 Classic Fuselage," BCA Structures TechTalk presentation, video recorded (internal only).

[14] P. Shawa, "Deeper understanding: Engineers trade computers for hand tools," Boeing News Now, May 1, 2018 (internal only).

[15] T. Wiley (2017). "The Making of Durability & Damage Tolerance," Boeing inSite inVideo (internal only).

IX. Biographies

Brandon Chapman is a lead engineer and structural analyst in the Structural Damage Technology (SDT) group, where he is primarily involved in the development of durability and damage tolerance analysis methods and allowables. He also enjoys teaching several training classes on behalf of SDT, both locally in the Puget Sound and across the Enterprise. In addition, he teaches an off-hours course on fatigue and fracture mechanics through the University of Washington (UW), as part of the UW/Boeing Certificate Program in Modern Aircraft Structures. Brandon holds a Ph.D. in Physics and a Master of Aerospace Engineering in

Composite Materials and Structures, both from the University of Washington. Prior to his employment at the Boeing Company in 2006, he worked as a research scientist at Brookhaven National Laboratory, at the National Synchrotron Light Source facility. Brandon has published papers in Science Magazine, Physical Review, Journal of Applied Physics, Journal of Crystal Growth, Environmental Science and Technology, and Chemistry of Materials. More recently, he co-authored several papers published in the Proceedings of the International Committee on Aeronautical Fatigue and Structural Integrity (Helsinki, 2015; Nagoya, 2017; Krakow, 2019). Brandon is currently a corresponding member of the ESDU (Engineering Sciences Data Unit) Committee on Fatigue.