AIRFRAME CERTIFICATION METHODS FOR UNMANNED AIRCRAFT

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AIRFRAME CERTIFICATION METHODS

The application of conventional structural certification methods to unmanned aircraft can lead to unacceptably long development times and costs that are out of line with the development costs for the airframe. Moreover, such certification methods often close the door on new technologies that could reduce the weight and cost of the vehicle simply because these technologies are not yet qualified for flight vehicles. The aircraft development community needs a different approach toward certification of these vehicles that ensures reliability and safety in flight, but requires less testing than the conventional building block approach used to achieve these goals.

The Boeing Company has had the unique opportunity to develop unmanned vehicles for a variety of customers, applications, and missions over the past few years. From vertical take-off to hypersonic aircraft, from flight demonstration vehicles to operational aircraft, Boeing has developed these aircraft for DARPA, the Army, the Navy, the Air Force, and NASA. The customer requirements, the qualification and certification requirements, and the mission requirements have determined the breadth of technologies available for these aircraft. This paper will summarize these various requirements and how they impacted the design space, structural concepts, and material selections for these aircraft. This summary will be the foundation for a recommended approach toward certification of unmanned aircraft structures based on the intended mission (single flight demonstration, multiple flight demonstrations, limited operational usage, or full operational usage).

The recommended approach for structural certification of these vehicles reflects its development cost, the lifetime of its service, and the performance requirements of its mission. Thus it will offer the ability to tailor the certification approach according to the projected vehicle usage. In addition it will provide a means for defining additional tests or analyses to aid in the user in certifying such aircraft for missions, lifetimes, or performance capabilities above and beyond its original design parameters. The approach will be bounded by the 1.25 static factor of safety proof tests used for single flight missile systems and the building block approach used with a 1.5 static factor of safety to certify composite aircraft structures for today's military aircraft. Results from the Air Force Composites Affordability Initiative (CAI) are presented that demonstrate how to reduce testing while meeting structural requirements.

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1.0 INTRODUCTION

Certification of unmanned vehicles poses a unique set of problems. These vehicles come in a wide variety of types and usages. As shown in Figure 1 just they run from shoe-box size aircraft to aircraft larger than most manned fighters. But these vehicles were originally designed to demonstrate a specific usage:

Some are one time use (missiles or drones),
Some are reconnaissance,
Some are bombers,
Some are strike platforms,
Most have had their original use expanded to encompass other needs.

Figure 1. Unmanned Air Vehicles Cover a Wide Breadth of Sizes and Usages

Most of today's unmanned vehicles were flight qualified - not certified. They were proof tested to ensure major component integrity for flight. Because they are now multi-use vehicles there is a desire to demonstrate their capability to meet the requirements for their usages – but users generally cannot justify the cost to certify the structures for low cost vehicles. In order to qualify these vehicles for flight very low cost methods were required to verify their structural integrity, not the intensive test methodologies used for certification for production programs (Figure 2). There is no extensive building block program or subcomponent risk reduction.

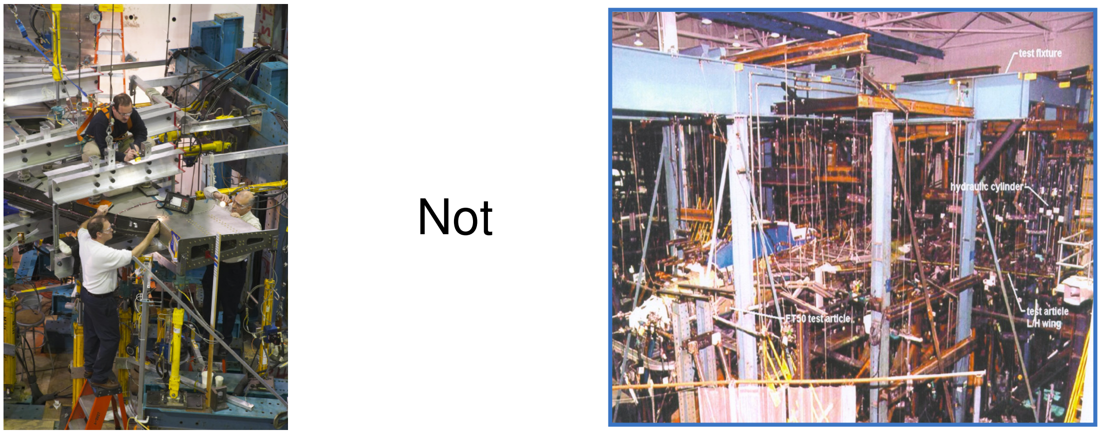

Figure 2. Simpler Test Methods Must Be Used to Certify Unmanned Vehicles.

Another part of the problem is that unmanned aircraft do not yet have a specific role in today's air force. We are still demonstrating and exploring the capabilities of these aircraft. Thus the roles of these aircraft are expanding into additional usages. Moreover, the demonstrated capabilities have created the desire to use these vehicles in the battlefield. In addition some have moved into limited rate production without certification in the traditional sense. Two well known examples of this path to production are shown in Figure 3. Because of these issues, unmanned aircraft have defined set of certification criteria against which they can be certified.

Figure 3. Global Hawk and Predator are examples of unmanned aircraft that went into limited operation before being certified by conventional structural test methods.

Because the flight structures of these aircraft are low cost, operators often cannot justify the cost of traditional certification approaches. Often the loss of a vehicle would not justify the test cost to preclude its loss. This is particularly true for the very low cost end of the unmanned vehicle spectrum, like those shown in Figure 4. Thus the problem we want to address in this paper can be stated as ***We need a low cost method that certifies unmanned vehicles for service that can be performed at very cost to the operator.***

Figure 4. Very low cost unmanned air vehicles

There is a very important second facet of this problem. Certification requirements (and design criteria) depend on projected use. Missiles and release-and-forget drones are typically qualified using lower factors of safety than aircraft. Prototype aircraft are qualified using tests that check major assemblies – often performed on flight hardware.

Production aircraft are certified using airframes set aside for that purpose. The process ensures that aircraft built to the specifications will perform as designed throughout its service lifetime. Unmanned vehicles pose a unique problem in that most have started out as prototype aircraft used to demonstrate a certain capability, then have had their use expanded in service. So a second statement of the problem is that ***We need a low cost method that can certify the structure for the design realm for which the vehicle is intended – prototype, design/demonstration, limited operational usage, or full production and fielded service.*** These usages are radically different and their certification methods need to be different and scaled to the projected usage.

As we consider the certification methods for these aircraft it is important to remember that the intent of the certification process is to reduce the risk for the user to fly the vehicle in his operational environment and accomplish the mission intended, Reference 1. With that in mind, it is helpful to recall that the amount of new technology that can be accepted at low risk varied with the maturity of the vehicle being developed. As shown in Figure 5, a prototype vehicle that will not be subjected to a rigorous certification test program might be able to accept technologies that a more mature production aircraft project could not accept without a complete risk reduction and certification program.

			Product Development Phases			
Technology Readiness Level	Readiness Level Definition	Concept Exploration & Definition	Demonstration/ Validation	Engineering / Manufacturing Development	Production/ Deployment	Operations/ Support
9	Production Flight Proven					
8	Flight Test Qualified	No Risk				
7	Full Scale Ground Test					
6	Component Level Ground Test		Low Risk	Medium Risk	High Risk	
5	Subcomponent Ground Test					
4	Panel Level Testing					
3	Proof of Concept Testing				Unacceptable	
2	Concept/Application Identified				Risk	
1	Basic Principles Reported					

Unmanned Air Vehicles
Have Been Limited
to This Regime

Figure 5. Most Unmanned Aircraft Currently Exist in the Prototype and Limited Operational Usage Mode.

Because these aircraft were prototypes and technology demonstration vehicles, they could accommodate technologies that were not mature enough for production programs at this time. This leads to the third facet of the problem.

Certification requirements (and design criteria) determine the maturity of the materials and structural concepts used in development of the vehicles. Prototypes can often use materials and structures that have low technology readiness levels. They are not certified but must meet flight qualification criteria (by test or similarity). More important they are qualified using the flight hardware and so the results of these tests reflect on the design, the fabrication process, and the manufacturing capability used with these materials and structures. But the test includes them all without relying on the building block approach so often used to assess production aircraft because the cost to certify each production aircraft would be excessive. Production aircraft are certified using test airframes and results are linked back to element tests that have statistical confidence levels and knock-downs that account for flight conditions (allowables). It is through tests of a few vehicles put through many load conditions that production aircraft are certified and that certification removes risk for applying the aircraft to the full range of service usage to which the aircraft was designed.

Unmanned vehicles pose a unique problem in that most have started out as prototype aircraft used to demonstrate a certain capability, then have had their use expanded in service. Moreover, there is a desire to provide a method that accommodates low rate production – that is sensitive to the difference between prototype, limited service usage and full production and service usage. This leads us back to a third variation of the original problem statement. ***We need a low cost method that certifies multi-use vehicles for service that is flexible enough to meet changing customer needs.***

2.0 AN EXAMPLE

Before going on into the proposed solution for this problem, let's examine a case history that helps to illustrate the point that the certification process can define the materials and structures used on unmanned (or manned) vehicles. In the case of Boeing's X-45A a number of new technologies were flown on these two technology demonstration aircraft. These new technologies included low temperature melt composite resins systems and foam core sandwich wings, as shown in Figures 6 and 7, Reference 2.

These technologies were not mature at the time that they were selected for use on these aircraft – there were no 'allowables developed, nor other flight vehicles flying at the time, although there were several in development that were examining their use at that time. It these technologies had been forced to go through the typical exhaustive materials qualification process or to have been put through the building block certification process, they could not have been used for the time and cost would have been prohibitive. But, because they were being considered for use on prototype vehicles that would each be ground test qualified before flight – regardless of whether they used these new material systems or not – we could implement these new systems using limited tests to determine 'design values.'

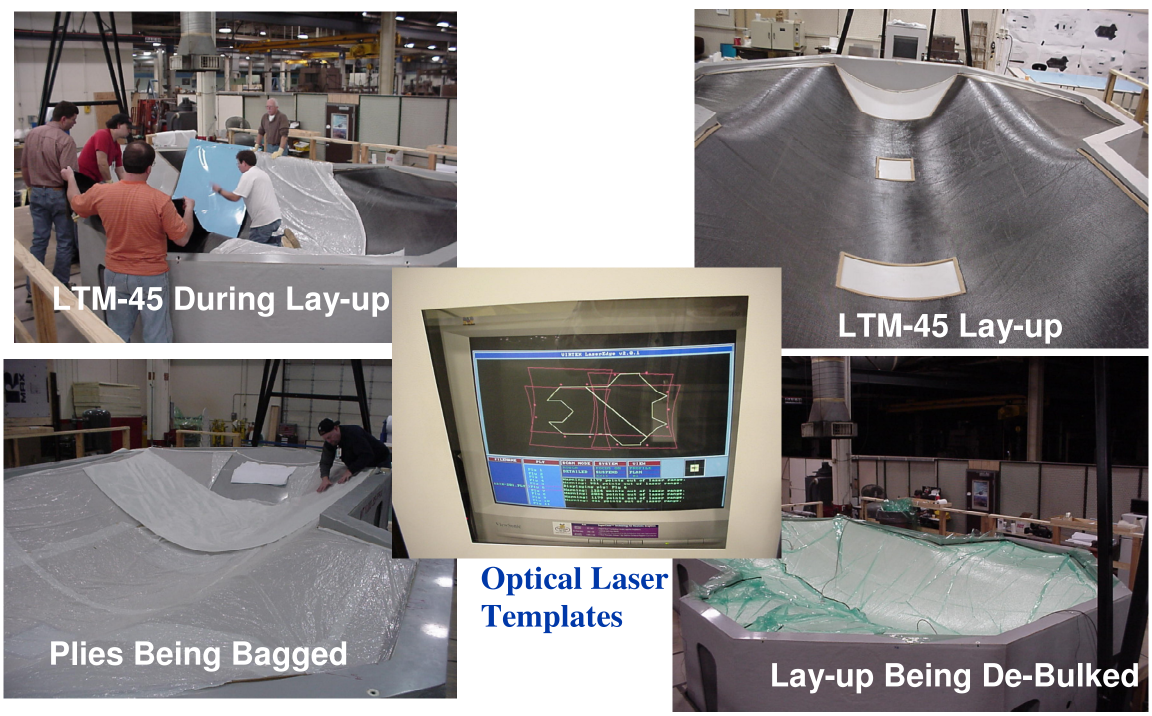

Figure 6. Ply layup for low temperature melt composite system for X-45A

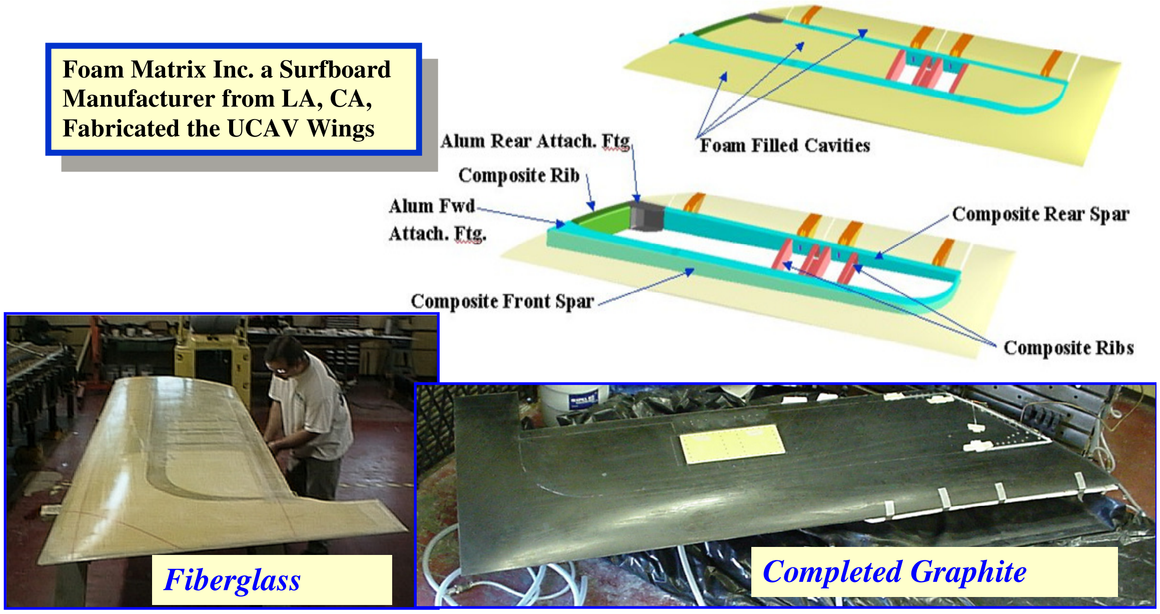

Figure 7. Development of the sandwich core wing composite system for X-45A

While we could accept greater risk for advanced technologies in demonstrators and prototypes in accordance with the assessment shown in Figure 8, the maturity of these systems was much lower than would be normally acceptable. Using the risk/readiness assessment tool developed under the DARPA/Navy/Boeing AIM-C Program, the risk levels for probability to fail the ground test was determined to be about 99%, if these systems were used without other efforts in parallel.

Foam Core Sandwich

Low Temperature Melt

		Probability of Not Meeting Static Strength Requirements									
		New Application					Existing Application				
		Primary w/o Cert.	Primary W. Cert	Secondary w/o Cert	Secondary with Cert.	Tertiary w/o Cert	Primary w/o Cert.	Primary W. Cert	Secondary w/o Cert	Secondary with Cert.	Tertiary w/o Cert
New Mat'l or Process	No Proof of Reproducible Props.	99.99%	99.9%	99%	95%	90%	80%	70%	60%	50%	40%
	Proof of Reproducible Properties	99.9%	99%	95%	90%	80%	70%	60%	50%	40%	30%
	Producer Spec	99%	95%	90%	80%	70%	60%	50%	40%	30%	20%
	Company Spec	95%	90%	80%	70%	60%	50%	40%	30%	20%	10%
Existing Material or Process	Tertiary Application without Cert.	90%	80%	70%	60%	50%	40%	30%	20%	10%	5%
	Secondary Application without Cert.	80%	70%	60%	50%	40%	30%	20%	10%	5%	2%
	Secondary Applciation with Cert.	70%	60%	50%	40%	30%	20%	10%	5%	2%	1%
	Primary Application with Cert	60%	50%	40%	30%	20%	10%	5%	2%	1%	0.1%
	Multiple Certified Applications	50%	40%	30%	20%	10%	5%	2%	1%	0.1%	0.01%

Fuselag

Wing

Figure 8. AIM-C technology readiness assessment process applied to new technologies for X-45A

But, the program performed two tasks that significantly reduced the risk to the program itself. To reduce this risk of structural failure for these components:

Design ultimate loads were increased by 125% beyond limit load (1.25 factor of safety x 1.25 additional factor). This decreased the risk of failing under peak flight loads from 95% to 25% (Based on historical certification data). And,

Every wing component was proof tested to 80% of limit load. This decreased the risk of failing under peak flight loads to less than 1% (Because the proof load encompassed the flight loads)

Thus the risk to the program was mitigated and these technologies were used safely and with good confidence. If this airframe had been forced to apply conventional building block certification processes and standard material qualification processes, these technologies could not have been used. We would have had to fall back to previously qualified material systems and previously certified structural concepts. While the performance and capabilities of the aircraft might not have been affected by this change, the knowledge of these two new technologies would not have been gained. Thus we need something between the flight qualification process used for prototype aircraft and the rigorous and expensive conventional certification process that would apply to the limited operational usage seen by today's unmanned air vehicles.

We need a low cost method that can certify the structure for the design realm for which the vehicle is intended – prototype, design/demonstration, limited operational usage, or full production and fielded service.

3.0 A PROPOSED ALTERNATIVE

Based on the problem statement presented and the example given, there are some ground-rules we can give for the formulation of a certification process for unmanned air vehicles. The certification process needs to include the following elements:

1) Take into account the flight qualification data already developed

2) Encompass the range of usage for which the vehicle is being proposed

3) Cost less than two airframe structures - Traditional certification costs run at least 6 times the cost of an airframe – often more.

4) Reflect the design criteria used and the use of design values (not B-Basis allowables in many cases)

5) Recognize that the certification process many reduce the envelope of loads, usage, or technologies available.

As shown in Figure 9, the conventional building block approach to aircraft certification covers a broad spectrum of usage and environments, many of which are rarely seen by most of the flight vehicles. The certification approach recommended herein is one that uses a stepped progression from the prototype vehicles to the production vehicles and does no more testing at any step than what is needed to assure safe flight and operation of the vehicle as it progresses from the prototype vehicle to the production of fielded operational vehicle, Reference 3. It offers an intermediate step that allows the user to qualify the aircraft for limited operational usage with much less testing that is performed for full operational usage, but more testing than is used for the prototype vehicle. The intermediate step is focused on assuring that the vehicle will operate safely in limited operational environment for a reduced lifetime consistent with that operation.

Notice also that the certification approach is linked to the factors of safety used in the design. It starts with a design ultimate load factor consistent with those which are used for vehicles certified by analysis alone. It would be anticipated that the flight envelop for such a vehicle might be held to less than half of this load for the prototype demonstration fights, Reference 4. As the program goes into limited operational status, the load factors would be allowed to increase and the test loads would encompass those anticipated for operational usage, but without testing the factor of safety to ultimate. The testing for limited operational usage would also include fatigue testing to two lifetimes of the limited lives expected for the vehicles and would be performed on the same test article that is used for the static testing. Additional GVT testing would be performed during this intermediate stage of certification.

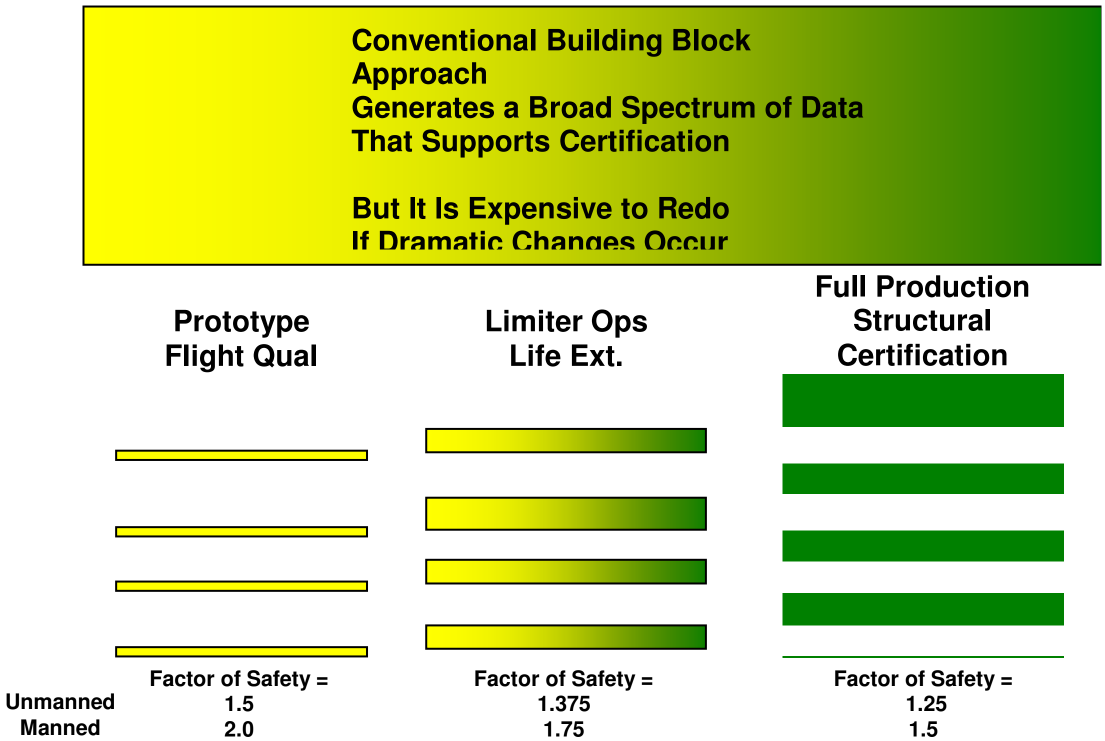

Figure 9. A comparison of the breadth and expense of a full certification approach to a stepped spiral certification approach

Testing to ultimate load is reserved for the full production certification in which such testing is used to not only validate the ultimate factor of safety, but also to encompass variations in manufacturing or assembly as well. In a well planned program, the airframe used for the final validation of the structure would be the same airframe used for the limited operational aircraft. However, if significant changes have been made between these generations, then additional airframes will be needed to accomplish the full certification test program. But, the intent of this path is to link the flight qualification of the prototype to the limited operational certification of the second step to the final certification of the operational vehicle. Thus the testing required to go from step two to step three is cut by half or more.

It is interesting to note that the proposed certification process used for this development is almost the direct opposite of what is used now as far as starting with small coupons and growing with the development to the overall airframe. This spiral certification approach is more aligned with the process of aircraft development than with structures development, as shown in Figure 10. Because the first aircraft is assumed to be a prototype or development aircraft it is assumed that it will be qualified for flight using a test of the flight vehicle. Subsequently the next stage uses a dedicated airframe to establish load limits and lifetimes beyond those intended fro limited operational usage. Then the final spiral takes this airframe (or one more like the final production design) and runs it through the full envelop of loads required to certify the production vehicle. And subsequently it would test the fatigue life and damage tolerance of the design in the same airframe.

Conventional	**Spiral Certification**
Builds up to Full Scale	*Begins With Full Scale*
From Materials	Flight Qualification
To Coupons	Life Extension
To Critical Details	Then Critical Details and Allowables
To Subcomponents	
To Components	
To Full Scale Test	

Figure 10. The spiral certification approach is run almost the reverse of the conventional certification approach

In constructing this spiral certification plan, we were careful to retain the current standards for certification of airframes when testing is not imposed. That is, we imposed a factor of safety of 2 between the design loads and the expected flight loads for prototype aircraft that would not be tested other than a flight qualification test. We did this by imposing a placard on the flight conditions so that the airframe would not see loads beyond 80% design limit load. That factor of two (or nearly) is consistent with today's certification process.

As shown in Figure 11, we also imposed that a full scale test to design ultimate load would be applied to ensure that the airframe would meet its design operating conditions for service. This is certainly consistent with current design and certification processes. In the chart we chose to show the conditions proposed for unmanned vehicles, an ultimate factor of safety of 1.25. That factor of safety is subject to discussion and controversy, but, even if this were not the factor of safety determined for use in unmanned vehicles, the process would not be impacted, only the design factor of safety would be impacted as shown in Figure 9. Certainly, the design ultimate load factor of 1.25 is consistent with missiles and other unmanned vehicles flying and in service today.

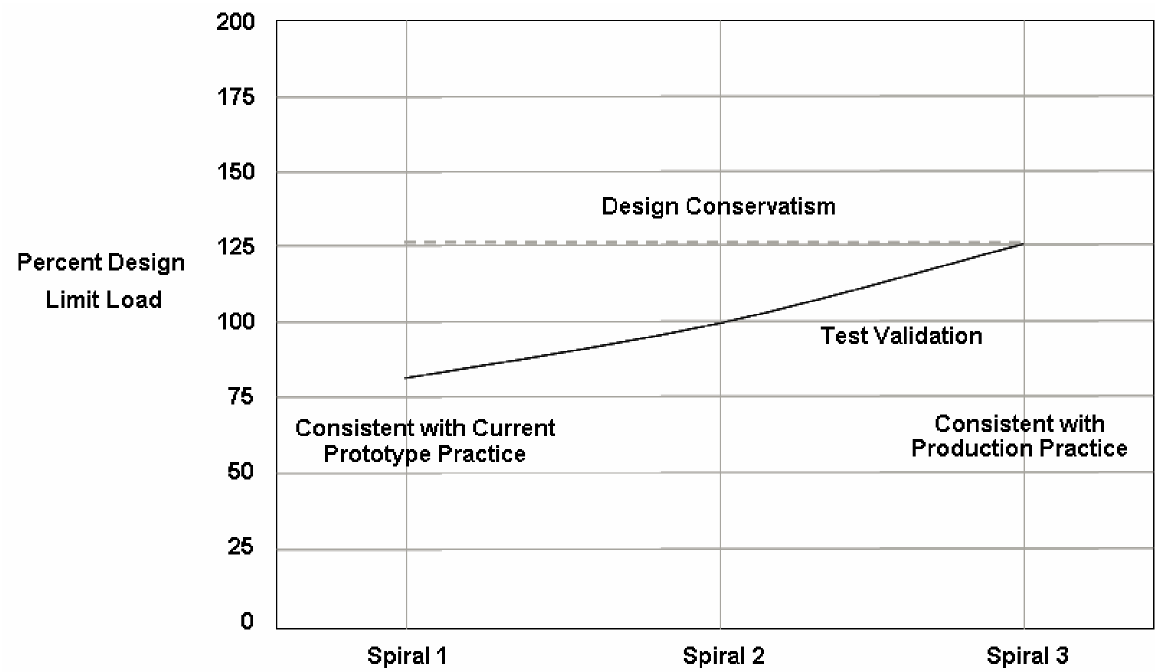

Figure 11. The spiral certification approach allows consistency between current practice for design of prototype vehicles (little analysis) and production vehicles (which are done primarily by analysis)

Further descriptions of the load conditions applied in each stage of the certification process are defined in Figure 12. In this summary we included the load conditions most often used to qualify a prototype aircraft for flight: A proof test to flight loads for wing attachments, a GVT to determine that systems and structures are not vibrating close to natural frequencies of the structure, taxi tests to get further dynamic load conditions, and flight loads monitoring to ensure that the loads recorded for various flight parameters are within the ranges predicted analytically. In the second spiral we included the fabrication of an airframe dedicated to structural testing. It is loaded to 100% design limit load to free the vehicle to fly within its design envelop. We included fatigue testing to twice the limited operational usage life to demonstrate durability. A more extensive ground vibration test of a flight vehicle to wring out systems in a greater array of environments (loaded and unloaded, for example). And flight loads would again be monitored to ensure that flight conditions did not exceed the bounds imposed by the reduced level of static testing applied to the airframe in test.

In the final stage of certification testing shown in Figure 12, we would complete the standard testing applied to production aircraft in their certification test program. This would include taking the airframe to its design ultimate load condition after an extensive fatigue test (from twice the limited operational life to twice the intended service life) and damage tolerance testing to one lifetime to demonstrate fatigue life capability with flaws. Finally, the design ultimate load conditions would be imposed on the airframe. At the same time payload and stores GVT tests would be performed on flight vehicles and a flight loads tracking program would be initiated in order to provide data for fleet management and individual aircraft tracking.

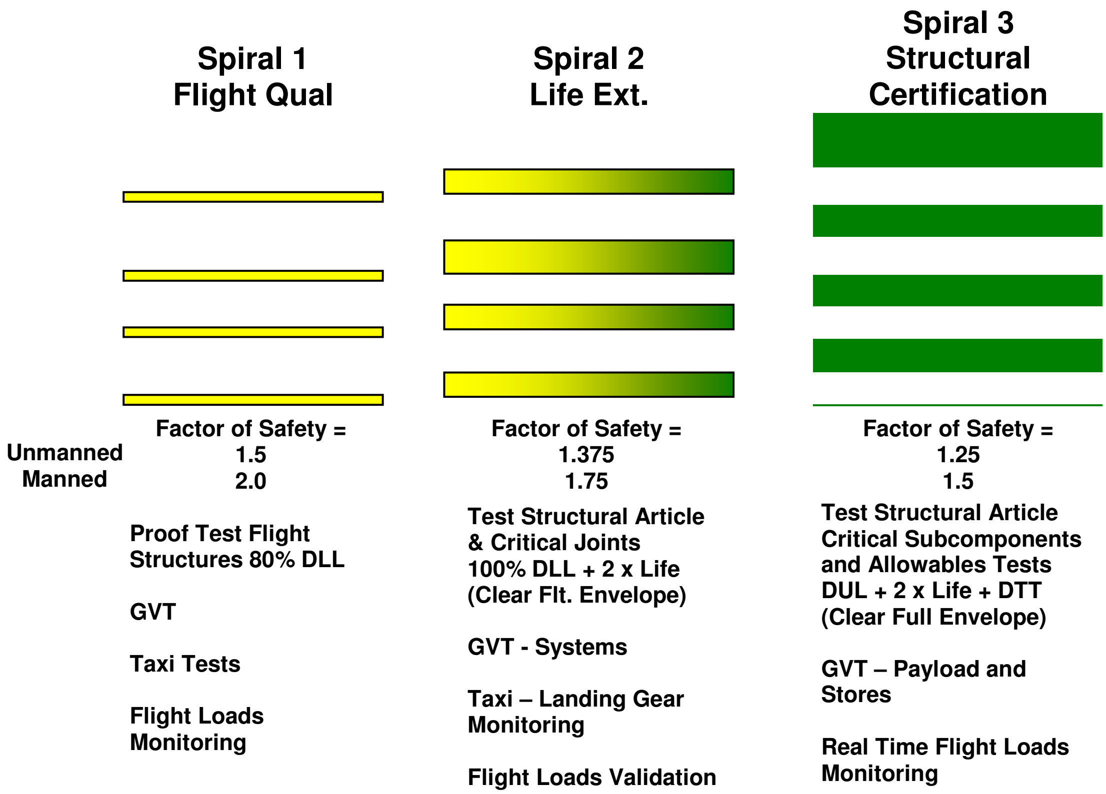

Figure 12. Further definition of the spiral certification approach.

Throughout all of these stages of certification, a rigorous approach to linking the system level requirements to the component and airframe level testing would be imposed so that the level of testing did not exceed the design conditions to be imposed, but also so that the factors of safety would not be exceeded. At the same time, limits imposed on the prototype and limited operational vehicles would have their own impacts on the system operation and service capabilities that would be fully documented and followed during service. This approach is shown schematically in Figure 13, in which requirements at each stage flow down from the system level requirements for each facet of the vehicle development (prototype, limited operation, and full service operation), and imposed limitations flow back up to he systems level to reflect the validated level of safe flight or operation to which the vehicle was certified in that stage, Reference 5.

There are two primary reasons why we feel that the proposed certification process can be safely applied to develop future aircraft systems (particularly unmanned systems). One of these is the capabilities of our current the structural analysis tools, Reference 6. Tools like those shown in Figure 14, are beginning to be validated for prediction of failure modes at the micro-scopic and nano-levels of behavior in our structures. As these tools are demonstrated to predict the impact of those failures on the macroscopic response of structures to flight load conditions, we are going to be able to determine exactly what testing is required in order to validate those predictions and to pin-point exactly what coupons develop the data required to make those predictions accurate.

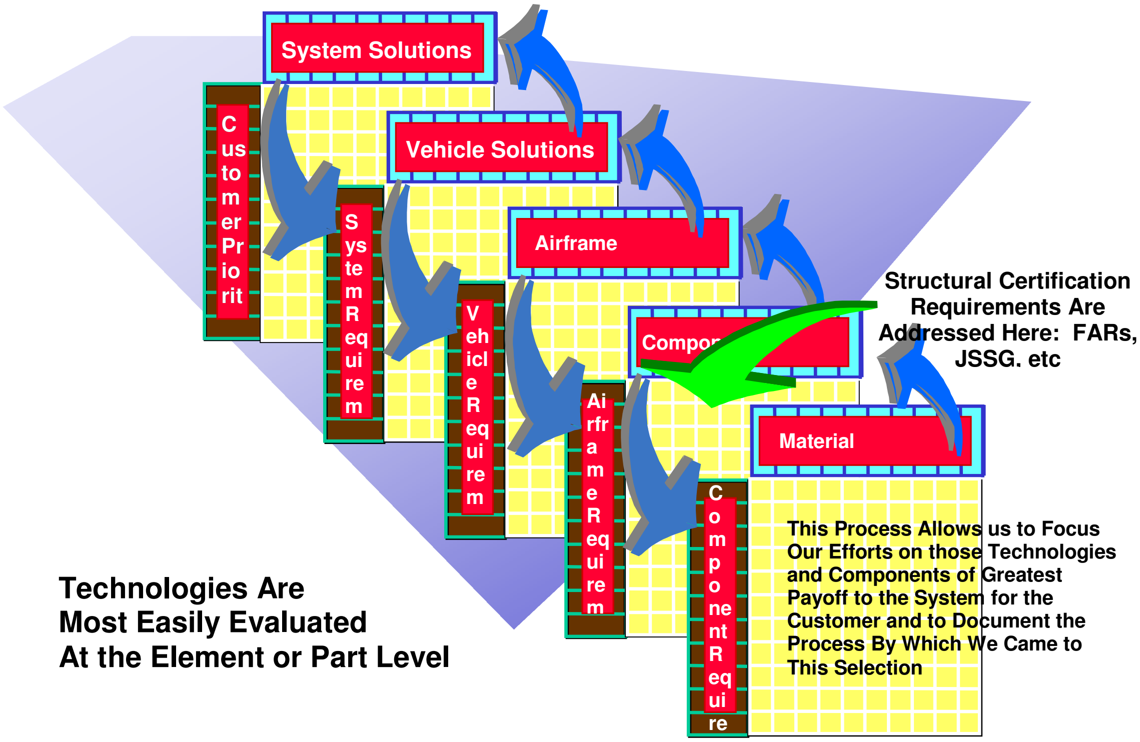

Figure 13. Requirements definition must be consistent between system level and component level Structural certification and materials qualification occurs at the part level.

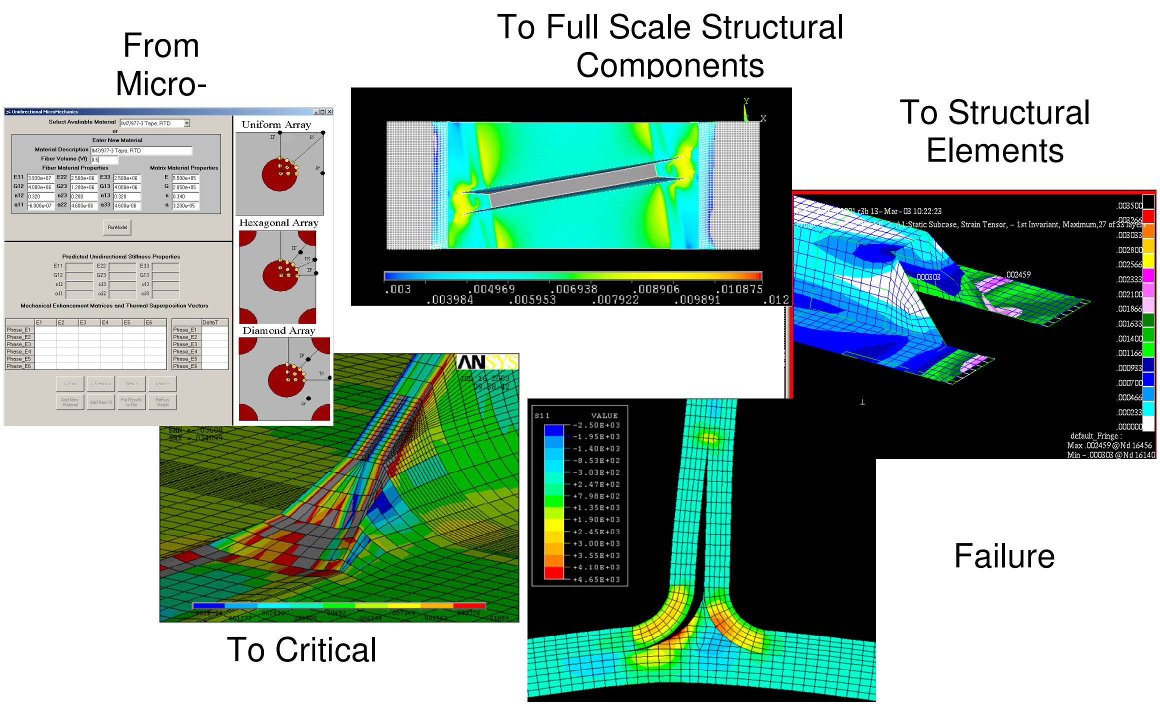

Figure 14. Analysis capabilities to define failure at lower levels of scale are improving dramatically – we seek what they tell us of failure mechanisms and failure mechanics

In addition to the accuracy and capabilities of our analysis tools, we are also beginning to exercise our manufacturing analysis tools (Figure 15) to tell us more about the as-fabricated state of the materials and structures from which components of the structure are made. Soon we will not only be able to determine the as-designed strength and fatigue life, but more important, the strength and fatigue life of the as-manufactured parts of the aircraft. It is the latter which defines the life and strength of the vehicle – even though it is greatly influenced by the design. In the distant past, we sought to model the as-designed structure with tools that were scarcely able to determine anything but the grossest responses of the structure, later we advanced to the point at which we were able to design structures very well with the analysis tools that we had, but we then struggled to deliver structures that mimicked those designs within some tolerance level. In the future, we see that the design analysis and manufacturing processes will be so closely tied that the analysis will be focused on predicting variations in strength and life due to variations in the as-manufactured structures. In some instances we are approaching this point even today.

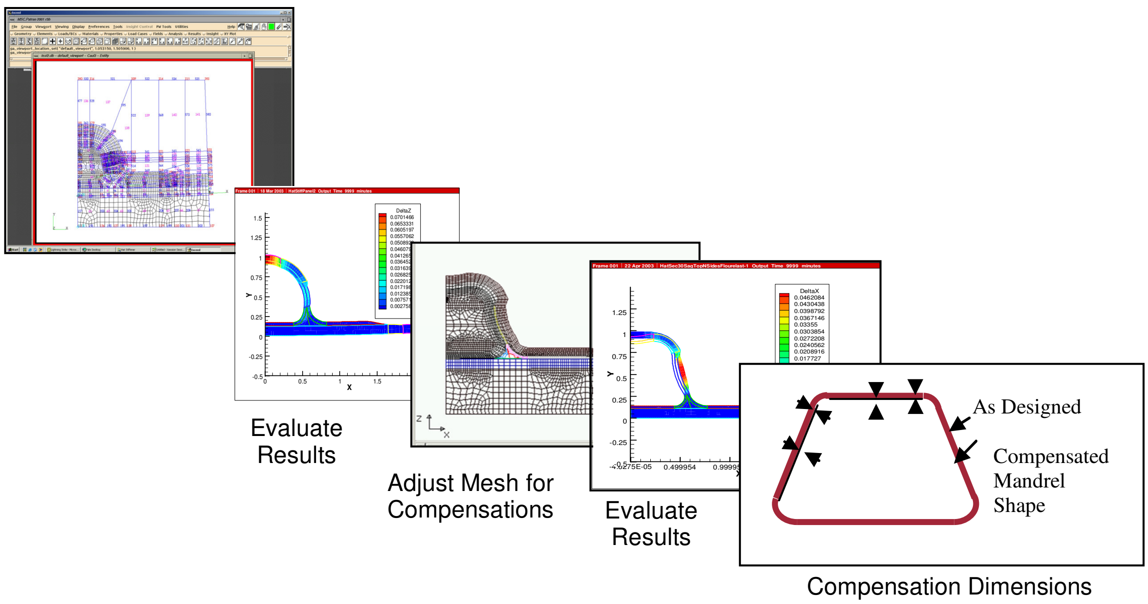

Figure 15. Analysis capabilities to define failure at lower levels of scale are improving dramatically – we seek what they tell us of the state of the as-manufactured parts

The whole purpose of both the recommended certification plan and the development of advanced and accurate analysis tools is to achieve safety of flight in advanced aircraft systems. We see certification methods going away from testing based methods supported and linked by analyses, to analysis –based methods supported by focused testing – testing defined by the data needs of the analysis tools as shown schematically in Figure 16. In the latter case the testing will not be done to supply a database that covered the entire range of design and environmental conditions, but to a few focused tests performed to ensure that the analysis methods were accurate in areas perhaps not completed validated previously. One would not have to completely revalidate the analysis as we do today so often in our current building block certification process. We as an engineering community are not there yet, but we’re getting closer.

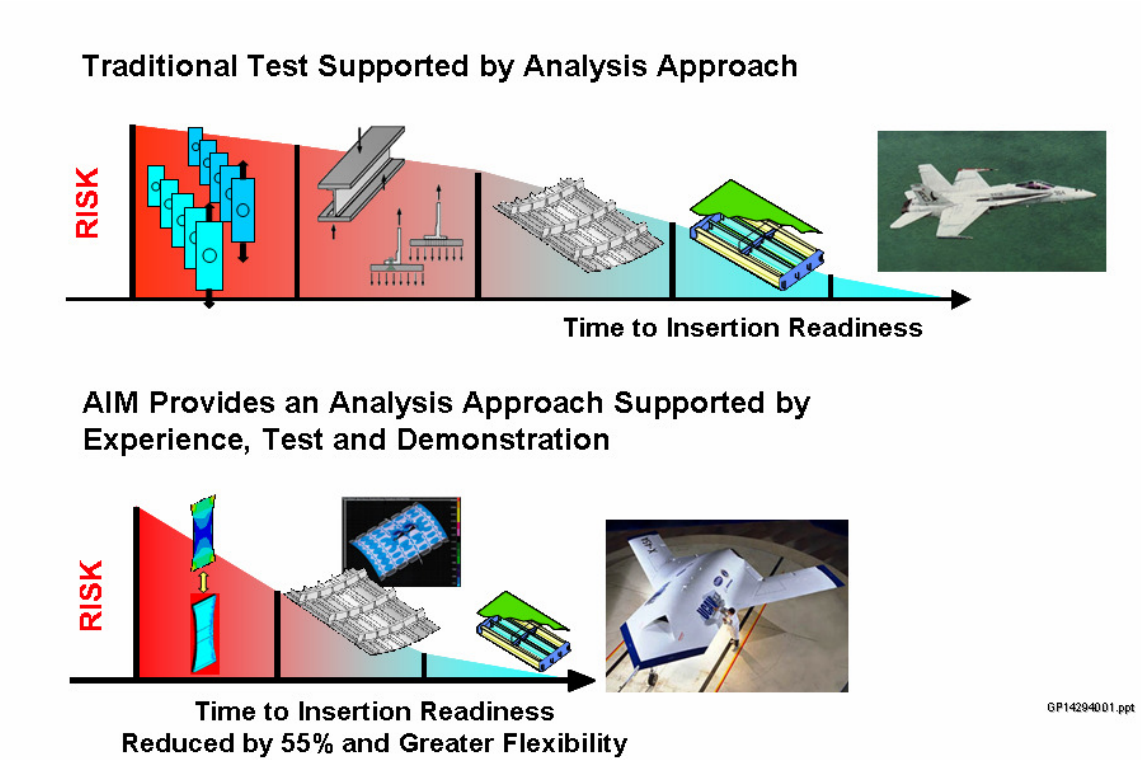

Figure 16. The goal is to develop analysis capabilities that will allow us to certify aircraft by analysis grounded in test, rather than test linked by analysis

But, the certification process proposed in this paper does not depend on the development or validation of these analysis techniques to be applied effectively. It can use today's methods. It has the advantage that it requires no more testing than is required today, it imposes no more risk to safety of flight than today's methods, but it offers much lower cost to certify a low cost vehicle for limited flight operations than today's methods which impose traditional certification processes on low cost airframes and at a price which eliminates interest in their pursuit. But, even more important, it is a method which ***can certify the structure for the design realm for which the vehicle is intended – prototype, design/demonstration, limited operational usage, or full production and fielded service. And the method is flexible enough to change with changing user needs as we said it must be.***

4.0 REFERENCES:

[1] Hahn, Gail, H., et.al., "Accelerated Insertion of Materials – Composites, Vol. 1 – Methodology," Boeing Report No. 2004P0020, May 2004.

[2] Schwedt, S. P. and Saff, C.R., Unmanned Combat Air Vehicle Advanced Technology Demonstration," Proceedings of International SAMPE Technical Conference, 34, Baltimore, MD, 2002.

[3] Saff. C. R., "Lean Certification for Spiral Development Programs," Proceedings of the Aircraft Structural Integrity Program Review, Savannah, GA, December 2003.

[4] Kan, H.P., Whitehead, R.S., and Codero, R., "Advanced Certification Methodology for Composite Structures," NAWCADPAX-TR-96-262, April 1997.

[5] Research and Technology Organisation, Corporate Author, *Qualification by Analysis,* Publication Pending, RTO-TR-AVT-092, 2006.

[6] Saff, C. R., "Lean Certification for Metallic and Composite Structures," Proceedings of the Aircraft Structural Integrity Program Review, Memphis, TN, November 2005.