Some Remaining Research Challenges in Aerospace Structures

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EXTENDED ABSTRACT

Throughout history some very beautiful, very large, very appealing, and awe-inspiring structures were built. The main objectives of these structures were that they should be durable, stable, and fucntional, with no regard given to weight. Structures like the Pyramids, the Coliseum, and medieval Gothic churches were all constructed before the advent of scientific based methods of design/analyis. Many times failure or collapse occurred, leading to a change in construction method to support a weak area but without any real understanding of why failure or collapse occurred.

As more modern structures were developed, the science behind analyzing and building these structures began to be laid out by legendary scientists such as Euler, Bernoulle (all 7 of them[1]), Gauss, Timoshenko (and his coauthors!)[1-9] and many others. The 20th centruy saw the birth of aviation and space travel, which required more advances in understanding structural behavior. The constraints on aerospace structures relative to weight, durability, performance, and damage tolerance are enormous and in many instances, in competition with each other. Performance

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requirements driven by other disciplines, aerodynamics, thermal behavior, pressure containment, extreme stability, are now the norm in high performance aerospace structures.

To achieve these objectives, many advanced analysis and numerical methods were developed during the past century. The advent of high speed computers accelerated and aided the development of these methods. The finite element method (FEM) was born in this environment. The first paper on FEM appeared in 1956[10] and simultaneous developments in the US and Europe[11] accelerated the acceptance and application of this method. The method grew by leaps and bounds [12-19] and became the workhorse of analysis methodogies, a position it maintains to the present day.

Finite element analysis systems have made astounding progress in advancing the modeling, analysis, and visualization of complex structures and structural components. A sophisticated three-dimensional (3D) model of structural components that would have taken an experienced engineer several months to model, analyze, and provide interpretation of results only a few years ago, can now be performed in a few days thanks to advancements in computer hardware, software, and integration of tools by commercial software developers. Figures 1 and 2 show recent examples of complex models of aerospace structural components. Figure 3 shows interactions of structures with other technical disciplines. - These technology advancements leads to the ability to perform multidisciplinary analyses of structural systems with complex interactions between and among differing physical effects such as aerodynamics, thermal performance, material property variations, and non-linear effects. These analyses were not possible a few years ago.

The current-day general-purpose, commercially available software packages such as NASTRAN, ABAQUS, ANSYS, ADINA, etc., enable sophisticated analyses with 3D complex models to be performed very efficiently and rapidly. Pre-processing (model creation), analysis set-up, post-processing and results visualization can now be performed rapidly, with increasingly efficient tools. Many of the early-career engineers of today are very proficient in the use of modern computers, computing engines, and these complex software packages. They are becoming increasingly efficient in building complex models of complicated aerospace components and are able to manipulate the general purpose programs.

Some trends and beliefs observed by the authors are:

- Investment into advancing *basic understanding of structural mechanics phenomena* and *behavior (design/analysis/test)* has waned in recent years.
- To those outside the discipline, structures is seen as a relatively mature technology. Strucutral behavior is well understood and methods and techniques currently in use are able to predict performance reasonably well.
- Expert analysts and designers may understand how advanced structures behave and how to adequately design them, but many junior engineers may not possess this knowledge. Mentoring of younger engineers has become more difficult in recent years due to loss of

older experienced mentors, and oversubscription of experienced personnel on critical development programs.

- The advancements in computing engines and software are allowing users *who have little or no background in engineering mechanics* to perform analyses and post-process the results of these analyses. *As such, the blind acceptance and quality of the interpretation of the results are two significant problems today*.

In addition there are significant shortcomings of the currently methodologies. They are summarized below:

Many physical aspects of structural behavior, as well as the underlying mechanics, are not well understood. Many techniques in and methods of current practice are derived from phenomenological observations and the application of empirical fits to test data. These empirical "laws" are then used as basis for design or assessment of a structural system. This process, many times, ignores or glosses over the lack of a detailed physical understanding of the actual physics-based process. As a result, designs could end up either overly conservative or un-conservative depending on the situation and the ability of the empirical relationship to mimic the actual behavior. New or significantly enhanced testing may be required when a new structural concept or application shows a new behavioral phenomenon.

This paper tries to examine several areas where lack of basic behavioral understanding is still lacking. These are:

1. Fracture behavior, where current methods are still based on observed phenomena and empirical curve fits to data. Fracture Mechanics needs several break-throughs:
   - Physics–based theories instead of phenomenological/curve fit methodologies. Paris' growth law of crack propogation is based on curve fitting of test data to determine the parameters to be used (Fig. 4)
   - Clear definition of boundaries of applicability of Linear Elastic Fracture Mechanics (LEFM)
   - Methods to implement Elastic Plastic Fracture Mechanics (EPFM) similar to those for LEFM
   - Mixed-mode fracture predictions. Currently the assumption is that most behavior is goverened by Mode I. Mode II and Mode III type behavior needs comprehensive studies to fully understand behavior of mixed-mode fracture and crack propagation.

2. Composite material models use simple rule of mixture relationships to arrive at bulk properties, treating fiber and reinforcement separately. The transition area of the fiber to matrix bond is not well understood or modeled effectively. Current trend is to perform extensive testing every time there is a change in fiber and matrix in order to determine material allowables, which is expensive and time consuming. Alternative methods to predict behavior of the composite are urgently needed. Also crack propagation and failure simulation and analysis (which has made

significant progress in recent years) still has difficutly with prediction of progressing failure, matching how the failure propogates through the laminates.

3. Advances in other closely related disciplines create new problems/opportunities for structures that need to be addressed. For example, new materials (functionally graded materials, Carbon nanotubes, etc.) require understanding of failure modes and boundaries of these failure modes etc. Another current example is additive manufacturing, which is highly process dependent. The type and amount of data necessary to collect affects the ability to determine the ultimate performance of the parts produced.

4. As the barriers of our current technology are crossed, new problems arise. For example, consider hypersonic flight and re-entry vehicles. There is an urgent desire to reduce mass by using materials that can perform both as structural members and as thermal protection. Investigation of such high temperature materials, especially those that undergo phase transitions or chemical reactions, as happens with ablating materials, requires models that can incorporate these thermal effects and translate them into structural material changes as the vehicle heats. This is a complex multi-physics-based interation which is difficult or impossible to test at full scale. How does one make predictions of full scale behavior from sub-scale coupon-like tests? New analytical and experimental methodologies needed to be developed and validated for problems such as these.

5. The expertise of engineers needs to be current, *both in old and new methodologies*, to be able to confront new challenges, and most of the time there will not be any precedents to look up and follow. Examples of current technologies that the engineers need to understand and be well versed in to confront new challenges include:
   - Nonlinear analyses. These are not a series of solutions of linear problems
   - Building block approaches to test and analysis
   - Verification and Validation methods

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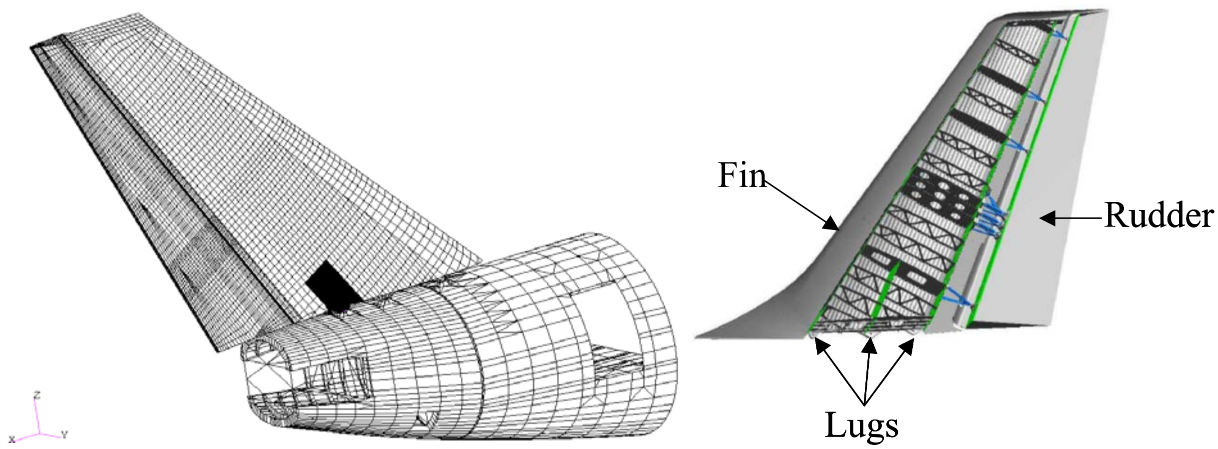

Figure 1. Complex model of an aircraft empennage

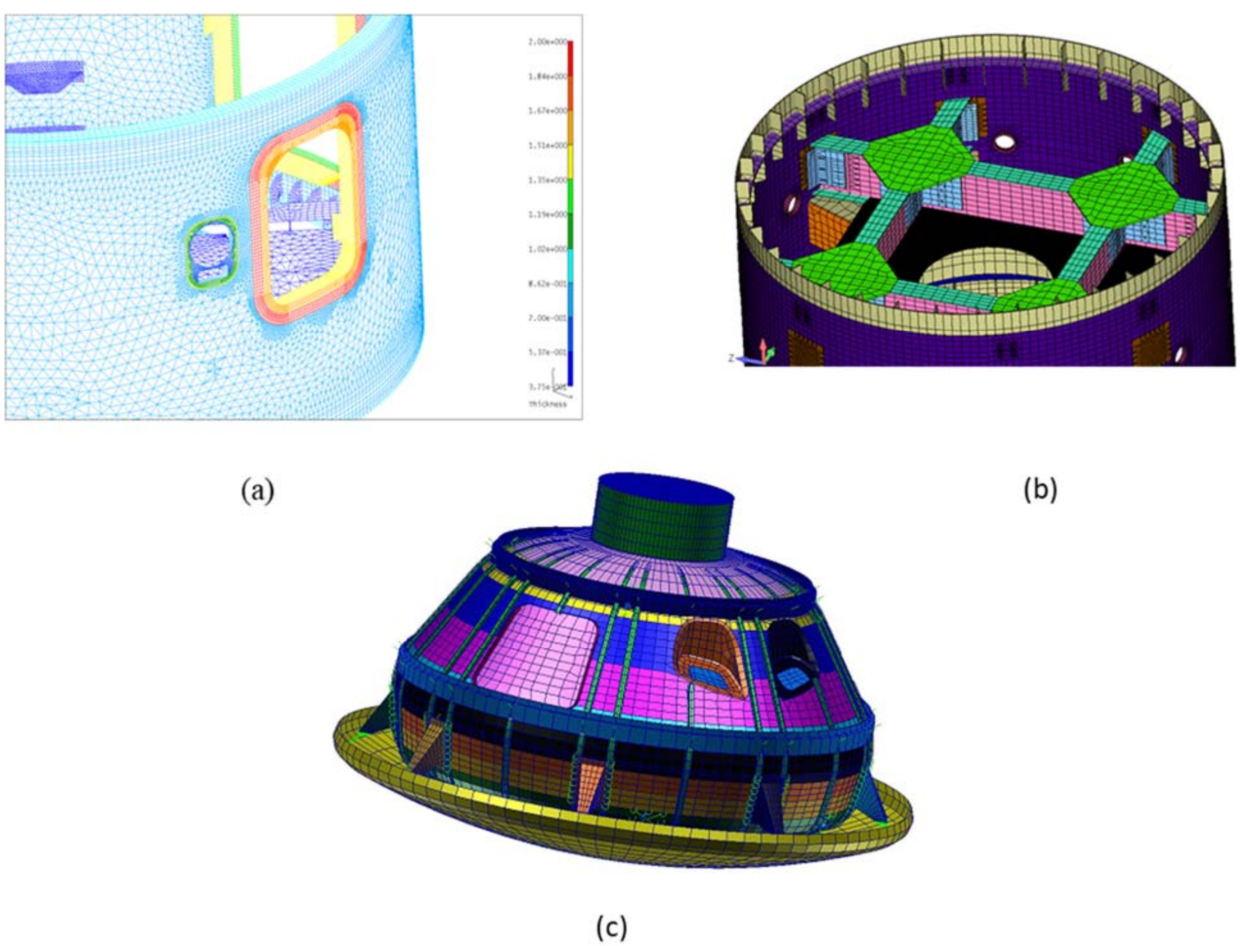

Figure 2. Examples of Complex Structural Models
(a) Reinforced cutout, (b) Complex internal structure, (c) Orion Crew Module

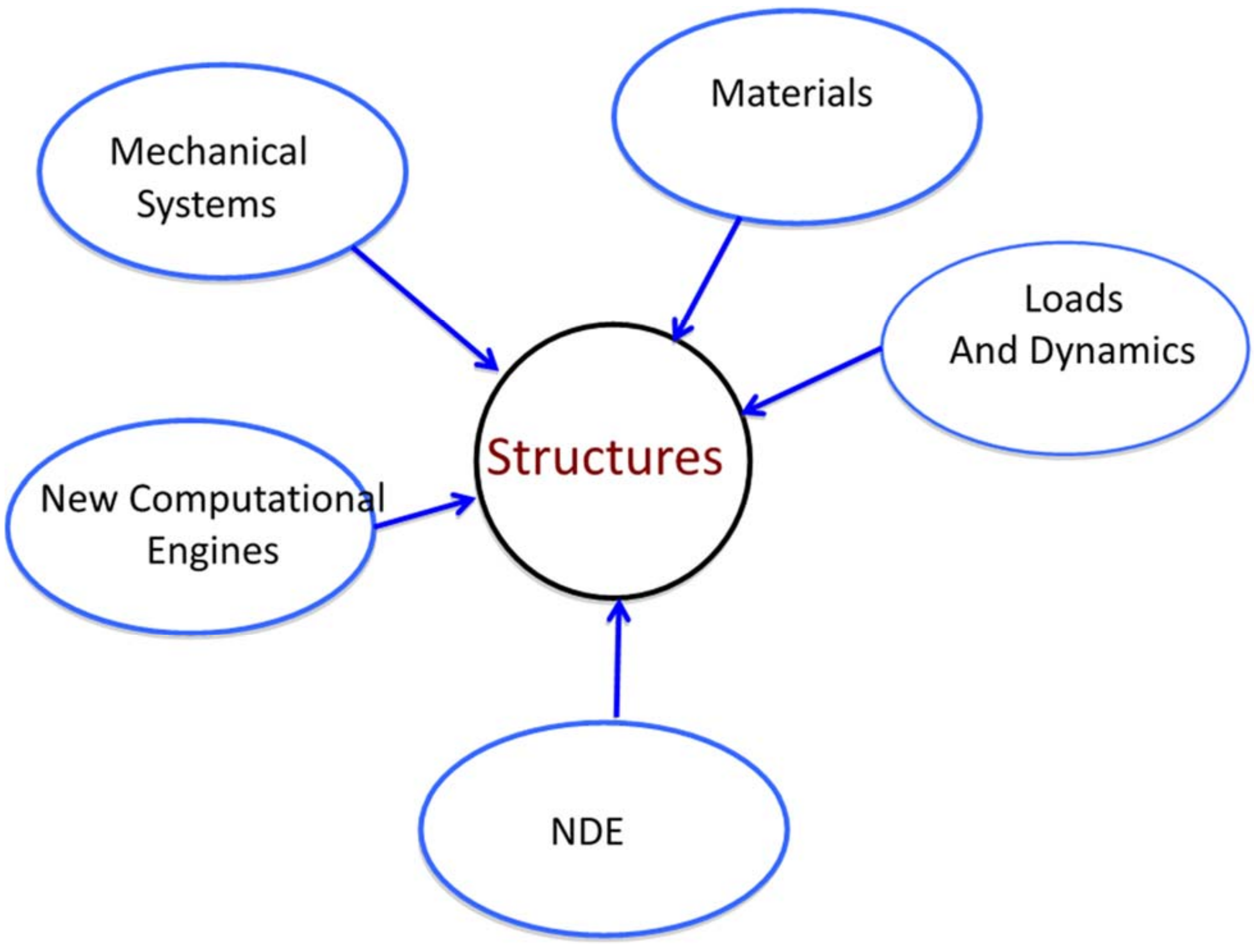

Figure 3: Complex interactions with other disciplines

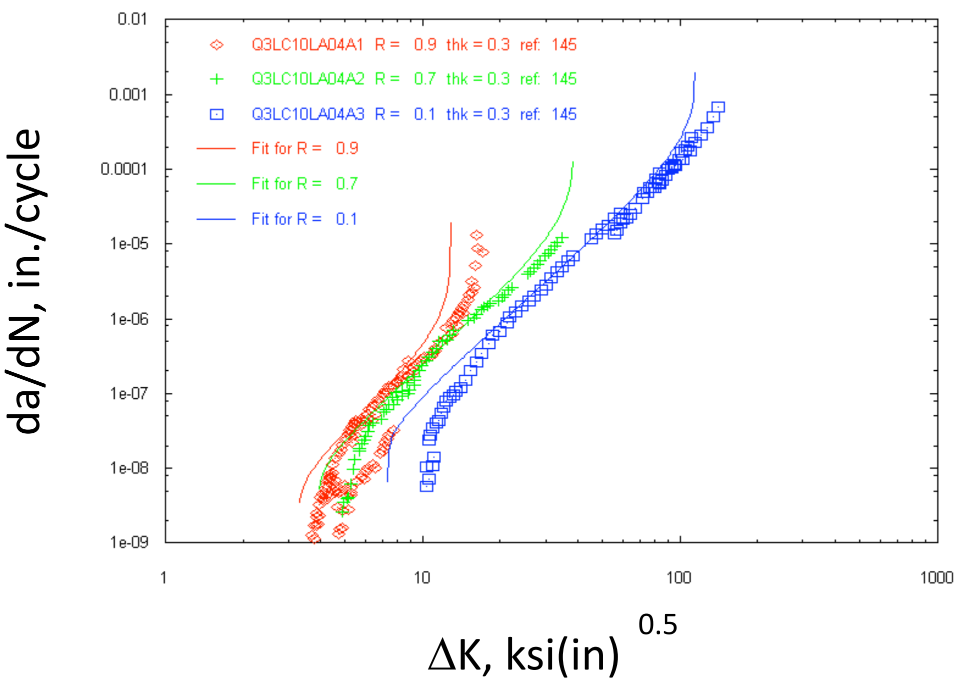

Figure 4. Typical fit to data for da/dN vs. ΔK (Paris' Crack Growth Law)