Some Remaining Challenges in Aerospace Structures

Kenneth R. Hamm Jr., NASA Ames Research Center
Kauser S. Imtiaz, NASA Johnson Space Center
Ivatury S. Raju, NASA Langley Research Center

AIAA SciTech Forum : 2021

STR-08 : Special Session in Honor of Dr. Stephen Engelstad III

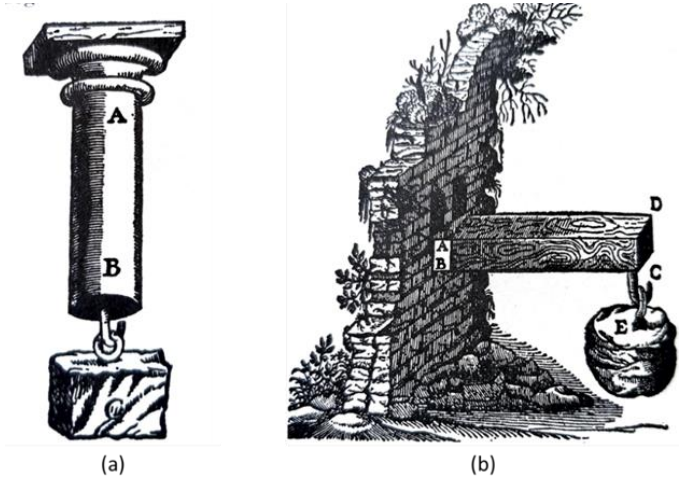
January 12, 2021

Introduction

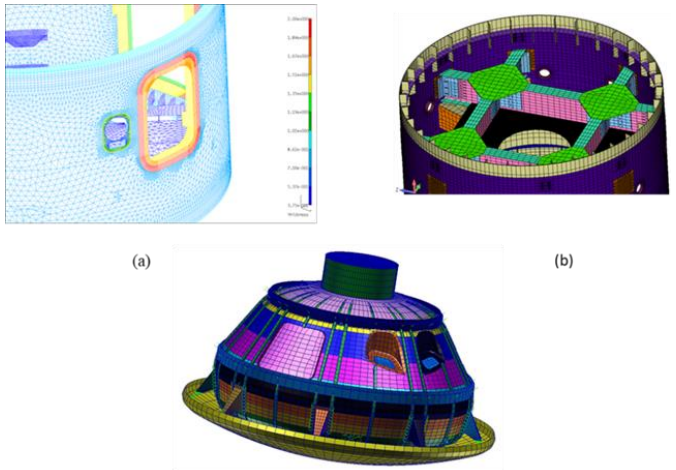
- Human History is marked with many impressive, awe-inspiring structures
  - Egyptian Pyramids
  - Roman Engineering
  - Gothic Churches
- All were built before the advent of modern structural engineering and a physics based understanding of structural systems
  - Knowledge handed down one generation to next (many times secretly)
  - Rules of Thumb
  - Build and hope the structure remains standing

Development of Structural Sciences

- Starting in the Renaissance, development of structural theories based on science were developed
  - Galileo (Beam Tests), Hooke (Springs), Euler and Bernoulli (Elastic curves), Navier, Saint-Venant, Mohr, Timoshenko (Elasticity Theory)
- Modern structures were developed in the 20th century
  - Advanced building structures (Skyscrapers)
  - Aircraft/Spacecraft systems
  - Driven by performance/weight/safety requirements
- Required new “numerical” based approaches
  - Finite Element Method born in this environment
- FEM is workhorse of current structural design/analysis
  - Ability to model many advanced structures and environments and some mutli-physics interactions



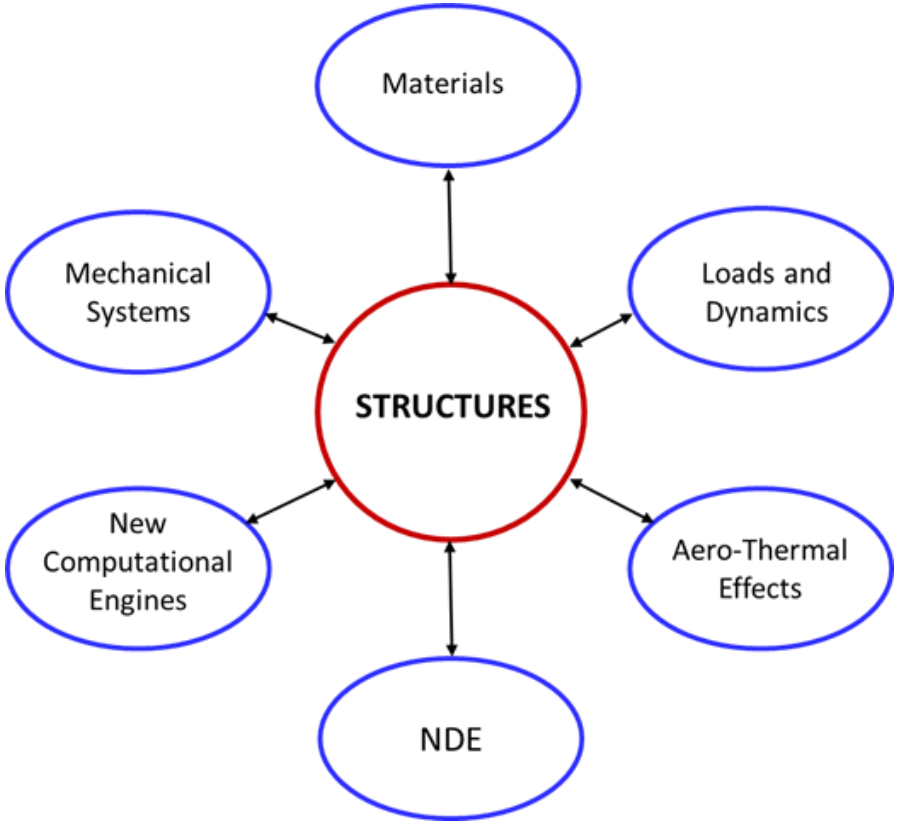
Galileo’s Proposed Tests



Advanced FEM Models

Remaining Challenges/Issues

- Still many areas in the Structures discipline requires continued research to keep pace with new technologies and demands
- Many sub-disciplines are still not mature
  - Lack of physics-based understanding in many areas and over reliance on empirical relationships
    - Empirical and phenomenological relations based on limited test results (modern “Rules of Thumb”)
  - New materials and manufacturing require new structural assessment techniques and tests
  - Multi-physics scenarios require interactions between numerous disciplines
  - Advanced computing engines require newer Verification/Validation methods
  - Mentoring the next generation of structures practitioners

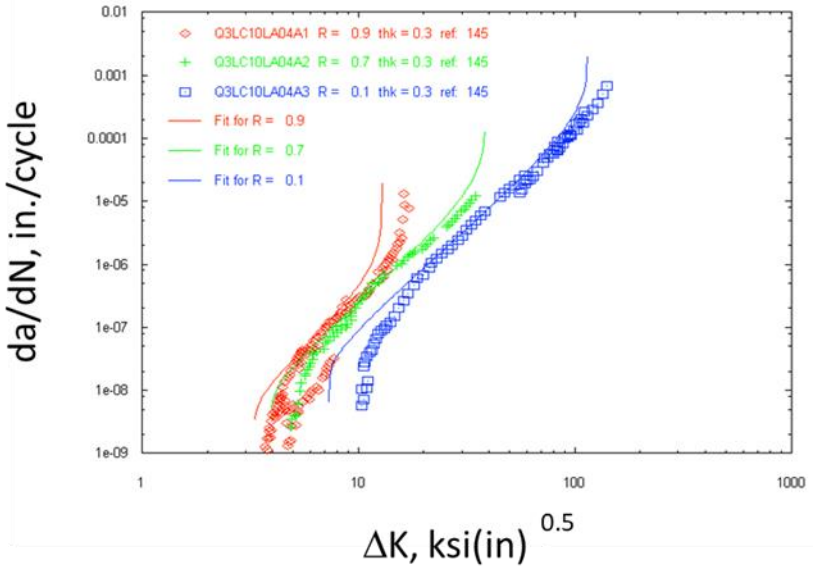


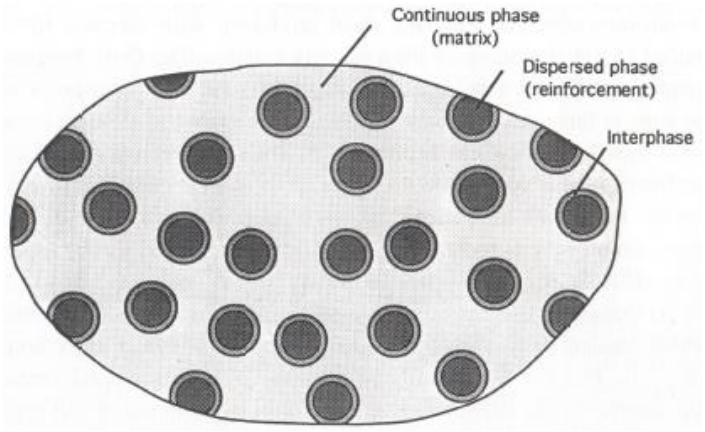
Interactions between Disciplines

Remaining Challenges/Issues

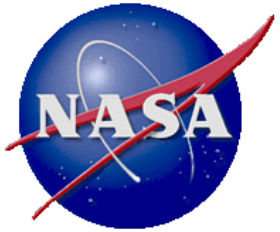
Key areas in Structures Discipline still needing additional research/emphasis

- Fracture Mechanics
  - Much behavior is phenomenological based on testing of small coupons and extrapolation to larger structures
    - Paris' Law example
  - Understanding of Mixed Mode fracture effects
  - Elastic Plastic Fracture Mechanics (EPFM) needs ease of use methods (Linear Elastic FM type)
- Composite Materials
  - Modeling of interphase regions where bonds between matrix and fiber exist and where fractures often initiate is difficult and not well understood
    - No physics basis for prediction of the behavior in the interphase regions
  - Extensive testing of fiber/resin combinations currently required to develop properties and failure modes





Remaining Challenges/Issues

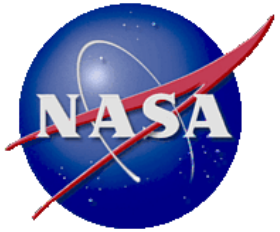


- New Materials
  - Carbon Nanotubes: Under development for many years
    - Now have ability to produce sufficient lengths and quantities for structural use
  - Functionally-graded materials
    - Structures where properties/materials change continuously to meet strength/life demands
  - Extensive research still needed to understand behavior and failure modes of new materials
- New Manufacturing methods
  - Additive Manufacturing (AM)
    - Highly dependent on processing method
    - How to deal with non-metallic AM parts
  - NASA has developed new Standard for structural AM parts, NASA-STD-6030
    - Requires significant testing and certification of processes
  - Much more research needed to understand behavior of AM parts for primary and secondary structure

Remaining Challenges/Issues

- New Applications and Interactions
  - Structural concepts may require multi-disciplinary methods to evaluate
    - Structural heatshields (Structures/Thermal)
    - Morphing structures (Structures/Aero/Dynamics), etc.
  - New analysis methods (multi-physics) required to fully understand complex interactions
  - Analysts require basic knowledge of other disciplines to be able to model effectively
- Computational Advances
  - Speed and capability of computer systems now allow for time dependent and nonlinear effects to be modeled
  - More rigor is necessary for evaluation of predictions based on time dependent and/or non-linear analyses
    - Mesh Size vs. Time Step, Detailed mesh vs. Rigid Approximations, etc.
    - Analysts need to have experience with advanced codes to be able to successfully implement solution strategies (Guidance from experienced users and practitioners)

Remaining Challenges/Issues



- Training and Mentoring
  - As more and more experienced personnel retire or leave the profession, more emphasis must be given to transfer of knowledge to the next generation
  - Up to date training in the latest methods and tools is a high priority
  - Mentoring of the next generation of structural engineers can be difficult
    - Many experienced personnel are oversubscribed and have difficulty setting aside time for mentoring
- Verification and Validation (V&V)
  - V&V of complex models and the results produced is currently not well documented and methods need further development
    - Many times each discipline does their own verification which may overlook complex interactions
  - Comprehensive testing is still required to accurately anchor model predictions

Illustrative Examples

- Important message to emphasize: <u>If engineers do not understand a failure mode they will not be able to design against it</u>
- Aloha Airlines Flight 243
  - After 89000+ flights, Boeing 737 fuselage structure failed in flight, skin fractured and separated, one flight attendant lost
  - Unknown failure scenario prior to this accident
  - Led to many advances in multi-site damage and aging aircraft concerns
- Space Shuttle Columbia
  - During launch, a piece of ET insulating foam failed and impacted the carbon/carbon leading edge of the orbiter, failing the panel
  - During entry, the hot plasma was able to enter the breech and fail the underlying structure
  - Loss of Crew and Vehicle
  - Failure mode not deemed credible prior to flight

Summary

- The paper has outlined many Structures issues that still need to be resolved and problems that need further research:
  - Many life and other prediction methodologies that are in current standard practice are phenomenological – effectively are curve fits to limited test data
    - New physics-based methodologies need to be developed
  - New materials require understanding of material behavior and implementation into structural math models
  - Vehicles for new missions pose new loading, environment, and other issues (many times interacting) that should be modeled and analyzed inter-dependently, not independently
  - Methodologies for Verification and Validation of complex interacting systems are immature and need further research
  - New test methods are needed for new materials, loadings, environmental issues, and new failure scenarios
  - Comprehensive simulation of time-dependent problems is still difficult and expensive and requires expertise to implement correctly
  - Finally, mentoring the next-generation engineers and providing up to date training is of utmost importance