Multi-scale Modeling of Airplane Structures

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Structural analysis models and simulations used in the design of Boeing commercial aircraft structure span length scales of 6 orders of magnitude or more (from 1,000's of inches down to less than 1/1,000th of an inch). At the small end of the scale, studies are performed where the objective is to predict the onset of failure in a single ply of a laminate or, at even smaller scales, to understand intra fiber / matrix interaction. At the large end of the scale, engineers assess the flight characteristics of the vehicle as a whole and compute the internal load distribution through the primary structural members (acreage skin & stringers, keel, spars, ribs, frames, etc).

The objective of these models differs, but they all play a role in supporting the analyses. At the large end of the scale, the vehicle level internal loads model is used to develop loads for analyzing the primary structure. A full airplane static test is performed with a representative subset of loading conditions to validate that the vehicle level model accurately represents the load paths of the manufactured structure. The vehicle level model sits atop a multi-scale foundation of models of increasing detail and fidelity meant to capture the behavior of the assembled components, parts, and materials to be used in the aircraft. At the core of this 'test supported analysis' approach are the methods and allowables used to design and size the structure. Much in the same way that the full airplane static test validates the vehicle level model, subcomponent, detail, and coupon testing substantiate the allowables and analysis methodology. From small scale to large, physical testing is used to substantiate & validate the structural analysis models.

This building block approach to modeling is used to analyze structure over the entire development cycle of a modern aircraft. In the early stages of development, the critical questions are those of feasibility of design. Answering these questions requires robust and flexible analysis methods for evaluating a wide range of existing as well as new & novel structural designs. If, as is often the case, the design is new, there may not be test substantiated models or methods available for a specific design. Given this, it becomes necessary to extrapolate beyond the existing test space with the use of detailed simulations, or 'virtual tests', to develop or extend a model/method's range of validity or facilitate the design of experiment for physical testing. As the development progresses, test data is gathered which leads to the replacement of virtual test data and/or validation of the virtual test models. Similarly, modeling of components in the vehicle level model may evolve over the cycle as subcomponent tests are performed and new behavior is observed.

Enabling continued aircraft performance improvement drives the need for higher fidelity and more integrated models early in the product life cycle. While the value of an individual model is understood today, potentially greater benefits can be gained from integrating those disparate models to enable acquisition of more complete and higher fidelity data sooner in the development cycle. Coarse, lower fidelity FEA models typically supply the loads and boundary conditions to drive higher fidelity component or detail level sub-models, and at the same time those sub-models can utilize the customized failure methods derived from material characterization simulations. This example illustrates an integrated multi-scale modeling approach. Achieving this level of integrated multi-scale analysis opens the possibility for multi-scale optimization and/or multi-disciplinary analysis & optimization which can guide configuration decisions early in development with lasting impact on the life of an airplane program.