Revisiting Building-Block Approaches for Structures

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The building-block approach is a method for building confidence in designs, working from lower-level components to more complex assemblies, using knowledge gained at each step to inform higher fidelity representations. The goals of this paper are to revisit the basic techniques of the building-block approach as it applies to structural design and analysis and illustrate some best practices that should be considered when developing structural analysis models. The paper demonstrates the process of leveraging existing information to build confidence in the design/development of analysis models, followed by examples of how the building-block approach for analysis was used in NASA hardware and spacecraft development efforts. The paper will also discuss virtual testing and hybrid simulation techniques, which are showing promise for more efficient/cost-effective verification of aerospace structures.

I. Introduction

The building-block approach is a method for building confidence in designs by working to develop understanding of behavior of lower-level components, then using the knowledge gained to inform representations of more complex assemblies. The approach is used extensively in the aerospace industry during development of critical hardware, flight vehicles, spacecraft, and other similar products. It can also be used to build understanding and confidence when developing mathematical models for complex structural systems. Applied in this case, the process starts with building

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understanding from lower-level and simpler modeling techniques, and then extending that understanding to inform and validate behavior at more advanced levels.

The goals of this paper will be to revisit some of the basic techniques of the building-block approach as they apply to structural design and analysis and illustrate some of the best practices that should be considered when developing any structural design or structural analysis models. The paper will also address new analysis and certification techniques, based on analysis instead of test, that are currently finding favor in the design/analysis community.

This paper will describe backgrounds of the building-block approach and how its concepts can be used to understand not only development of hardware, but also development of numerical models, starting with simpler representations and working towards more high-fidelity simulations of behavior. The paper will concentrate on the analysis aspects of the building-block approach and demonstrate the process of leveraging existing information to build confidence in the development of analysis models. Examples of how the building-block approach has been used in NASA hardware component and spacecraft development efforts will be presented. Finally, the paper will summarize some of the best practices for building-block implementation in aerospace structural model development.

Even though traditional building-block approaches typically combine component physical testing and test results with analysis model development, the testing aspects will not be tackled in this paper to any great extent. Some of the examples may refer to test verification of component models, but the main emphasis is to stress the development of understandable and reliable models, using simplified assumptions and calculations to build confidence in an overall analysis strategy for aerospace structural modeling.

II. Historical Background

As stated earlier, the building-block approach provides a basis to build confidence not only in a structural design but in the analysis as well. Starting with simple mathematical representations and building to the more complex provides understanding of behavior that is often hard to discern from a single-step approach. This lesson is sometimes lost in today's environment of widespread Computer Aided Design (CAD) software with their ability to capture and model many detailed features, resulting in complex three-dimensional (3D) representations of structural systems. The authors have observed a tendency to develop complex models *far too early* in the design process. Managers sometimes desire having "all the answers" before a program or project even begins, which leads to an overly detailed design level of complexity just to justify a program selection. Figure 1 shows guidelines for project development that have existed at NASA since the 1960s. The green highlighted boxes are areas where structural design/analysis involvement is usually necessary. Work begins with establishment of requirements, leading to preliminary sizing to ensure the goals and objectives can be met. Work then flows to final detailed design. This flowchart demonstrates the need to build confidence and understanding of design requirements and their effects on overall structural behavior before launching into detailed design evaluations.

Developing complex models too early can trap a project on a particular solution path, which may or may not be the best or most optimum design, due to lack of understanding of the basic interactions between and among structural parts. Overall performance questions, such as where do loads go, how best can a structure be stiffened or softened, and selection between structural concepts, are best answered with simpler mathematical representations, not complex ones. *Complex models at these stages are not necessarily high-fidelity models and are certainly not always good or accurate models*.

The building-block approach is a key method for ensuring quality analyses are developed that meet requirements. The complexities of lightweight, built-up structures led the aerospace industry to develop the building-block approach. Typical implementations start with low-level, coupon-level representations to gain basic understanding of behavior and gradually build up to more complex part-level, assembly-level, and system-level representations. At each level, an understanding of behavior and characteristics is obtained that can then be used to inform the next level of complexity.

The concepts can also be applied to development of mathematical models. Lower-level models inform more detailed models and they in turn inform assembly models. Both strategies (Hardware and Analysis) are illustrated in Figure 2.

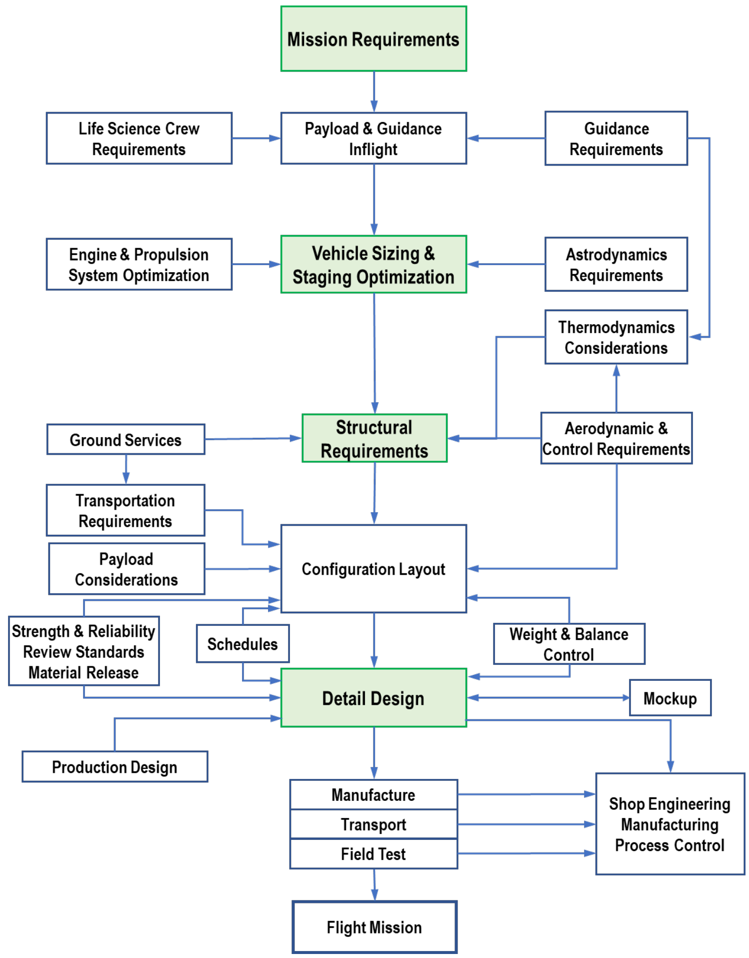


Fig. 1 Mission Development Flowchart Reproduced from NASA-SP-65 [1]

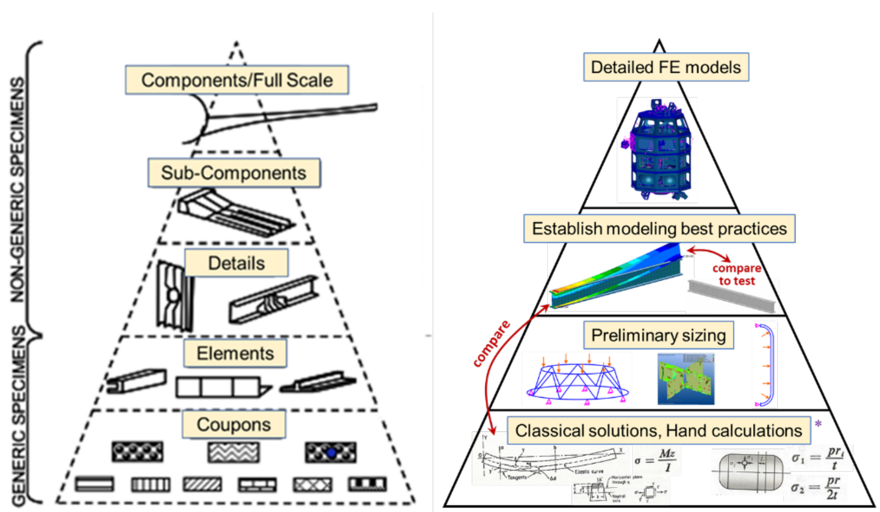


Fig. 2 Comparable Building-Block Development for Hardware vs. Analysis Models *[2, 3]

Often, proceeding to the next level of complexity is accomplished by linking modeling strategies to results of an experimental test program. However, this can also be achieved by using simple mathematical models to gain basic understanding. In both cases, the modeling strategies and fidelity can then be incorporated into higher fidelity models at upper levels of assembly. Key questions that can be addressed with simple models are: what is the overall stiffness of a piece of hardware, how much overall deflection can be anticipated, and are parts better represented with lower-level elements (beam or plate types) without sacrificing any of the required behavior. Lower-level elements tend to be easier to understand and easier to adjust as design changes are required. Cross-sectional properties and/or plate thickness distributions are relatively easy to change. However, changing geometry and configuration for a 3D representation requires new CAD and often complete remeshing to accomplish the same result. Additionally, new CAD may also trigger the need to redefine boundary conditions, material property assignments, loads, and other features of the finite element modeling.

Many past studies and papers have demonstrated the usefulness of building blocks in aerospace disciplines. Building-block tests are commonly employed in aircraft and space vehicle development and are known to effectively reduce technical risk and development cost. These approaches rely on analyses and tests of basic elements and subcomponents to establish the effects of local details and internal load paths on structural behavior. They also can address manufacturing scale-up issues as shown by Rouse et al. [4]

A building-block analysis approach begins with basic elements and builds in complexity in a systematic and progressive manner. Such an approach permits each step in the process to be verified and its influence on the overall response determined. The hierarchy of the analysis building-block approach is presented in detail in Figure 3. The final results are presented to external reviewers and the stakeholders, engineering reports are written, and the entire effort is subjected to rigorous peer review. If necessary, the process may be repeated from any of the building-block steps.

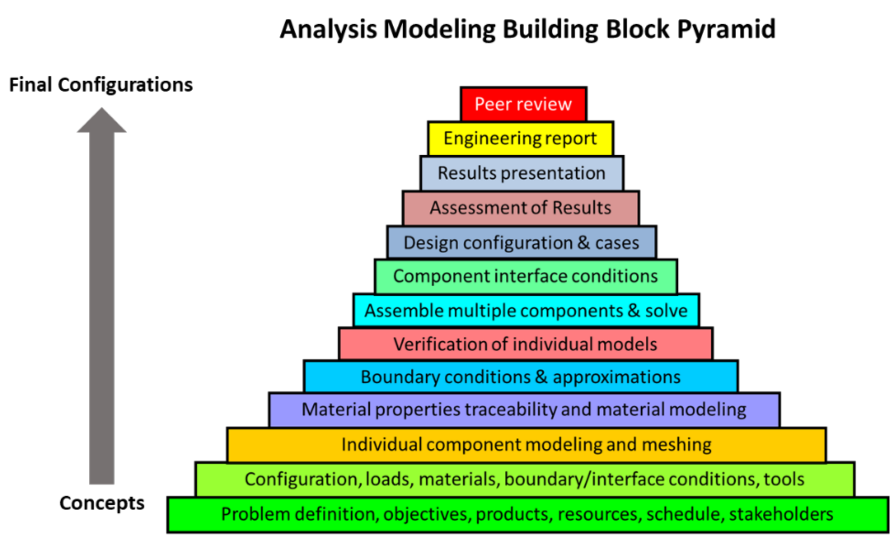


Fig 3. Analysis Model Development [5]

This building-block analysis approach provides different entry points for analysts, stakeholders, and external reviewers. Analysis assumptions can be challenged and revised, analysis findings can be compared to observed behavior, and bounding responses can be determined; and the analysis end products have technical rigor and their applicability limits defined.

Testing is one sure way of uncovering unexpected failure modes. Matsumara et al. [6] outline a key philosophy of building-block tests, namely that discrepancies between analytical prediction and actual behavior need to be discovered and evaluated as early as possible. The lower the structural complexity, the more easily failure cause can be identified and isolated. Also, at lower complexity, the cost of making test specimens is lower, so statistical knowledge about structural integrity (such as material property distribution) can be obtained efficiently with a large number of specimens. If testing or verification is delayed and an unexpected critical failure is found at a later assembly stage, redesign across the system and schedule delay may be inevitable, and in turn, have a severe impact on the project.

Norwood et al. [7] presented lessons learned from the survey of legacy building-block test program experiences. Verification and validation of the damage prediction methods employed is essential. The scope of full-scale tests can be reduced or eliminated using damage prediction methods that have been verified and validated as shown by Selvarathinam et al. [8]. It is important to include the critical failure modes in the damage model *rather than attempting to include all* the possible failure modes. The effects of other failure modes can be included as a correction factor, which is correlated to test data at the subcomponent level. Other works by Harris et al. [9], Selvarathinam et al. [10], Knight et al. [11], and Raju et al. [12] give additional examples and overviews of the approaches that are commonly used.

The main ideas of the building-block approach as it applies to structural modeling and analysis can be summarized as follows:

- Understanding should start with development of aspects that need to be captured in analysis. This may be achieved by investigating classical solutions such as utilizing those found in Timoshenko [13], Roark [14], and Pilkey [15] to gage expected result ranges and magnitudes.
- Use <u>appropriate model fidelity</u> for the level of development in the process. Early on, Beam or Shell models may be appropriate to assess early conceptual development. These should gradually evolve into more complex models (if appropriate) to capture more detailed behavior.
- Beam elements are appropriate when the structural behavior involves tension, compression, and/or bending of long regular elements. In fact, using higher fidelity elements in cases like this may lead to incorrect answers (e.g., plate or solid elements to model beams). In these cases, the more complex mesh can lead to large models that are difficult to validate and hard to interrogate, where simpler representations can lead to much easier understanding and visualization of behavior.
- Plate/Shell elements can be appropriate where thickness behavior can be simplified or when plane stress/plane strain assumptions hold. Again, these models are simpler to understand as far as identification of displacement and stress fields are concerned.

Detailed hardware development usually starts with material coupon level tests, proceeds to component level tests, then to assembly tests, and finally to full structure. Modeling should follow a similar path. At each level, (high-fidelity) analysis models can be created and correlated to the results of hand calculations or lower level analyses. Simplified correlated models that capture desired behavior can then be developed from these high-fidelity models. These simpler correlated models can then be used in the next-level assembly. Using this process, confidence in both the design and analysis is built into each level and understanding of behavior is gained from the observations of lower-level analyses.

In addition to the classical building-block approach, other types of modeling can give good representations of "regular" structures:

- Axisymmetric modeling can be used to develop significant detail over a cross section, assuming the structure is symmetric about a central axis. Axisymmetric models are usually easy to develop and solve. Complex loading can still be applied, assuming the loading and boundary conditions meet the requirements of axisymmetric theory.
- Half/Quarter plate/solid modeling of a structure with appropriate boundary conditions (symmetric/antisymmetric) can be a powerful method of representing a structure with internal symmetry. Only modeling a half or a quarter of the structure may allow for easier changes to geometry during design iterations.
- Spring elements with proper load/displacement behavior can be used to simulate joints instead of including full 3D representations of fasteners and contact surfaces. These should be linked back to more detailed component analysis models to assure proper behavior is being captured.

Results from these types of models can be used to inform component or system models at a higher level and may negate the need for complex 3D models if the simpler representations can achieve understanding and allow for validation of behavior. The next section provides examples to illustrate some of these major points.

III. Examples

To illustrate some of the points raised regarding use of appropriate model fidelity and simplified representations, the following four examples are presented.

- Example 1 illustrates the need to understand overall behavior by starting with simple models to determine how modeling strategy can affect solutions. An example of a simple cantilever beam problem is presented.
- Example 2 demonstrates how other simplified modeling techniques, such as axisymmetric modeling, can be used effectively.
- Example 3 illustrates an intermediate fidelity modeling approach, where defeatured[1] meshes can be used to make rapid studies of design changes/features without requiring detailed remeshing of the entire geometry.
- Example 4 provides more of a complete analysis development scheme, where initial sizing is accomplished using classical tools, followed by models to understand behavior of complex components. Simplified representations of complex behavior can be folded into upper-level design validation models via use of beams or springs with appropriate load-deflection behavior.

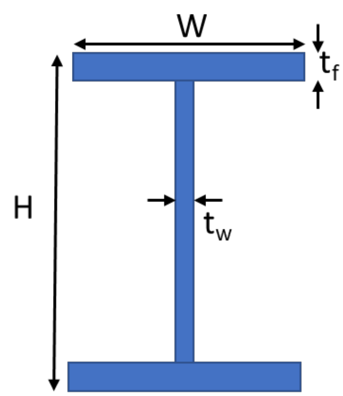
A. Example 1- Develop Understanding Through Use of Simple Models or Representations

Use of simplified analyses can build confidence in the analysis methodology chosen. Every student of structural engineering and analysis knows the need to develop confidence in FE meshes. Mesh refinement and convergence studies are the primary method for achieving this confidence. To illustrate how understanding and confidence can be 'built up', consider an example of a simple cantilevered I-beam, fixed at one end, loaded at the tip. Assuming the properties in Table 1, a series of analyses are conducted using different approaches, from a classical hand solution to various FE mesh representations. The mesh models used are shown in Figure 4. As shown in Table 2, the various modeling techniques produce very different sets of answers depending on how the analysis model is constructed. Even though all the representations are good at producing tip deflection results, a coarse mesh of plate elements can be very unconservative in stress determination. Even a finer mesh of plates may require significant refinement to approach the level of accuracy provided by a simple beam representation.

Table 1. Cantilever Beam Properties

Assumed Beam Properties	
Length	100 in.
End Load	10 kip
Material	Aluminum

Cross Section Dimensions		Calculated Section Properties	
H	10.0 in.	A	7.25 in^2
W	5.0 in.	I11	128.1042 in^4
t_f	0.50 in.	I22	10.4284 in^4
t_w	0.25 in.	I12	0.0 in^4
		J	0.466458 in^4
		K1	0.310345
		K2	0.574713



I-Beam Cross Section

[1] Defeaturing: The process of suppressing details present in CAD (such as fastener holes, fillets, bend radii, etc.) to produce simpler forms of geometry, more appropriate for meshing initial concept models and analyzing overall structural behavior, where these smaller details have little or no effect.

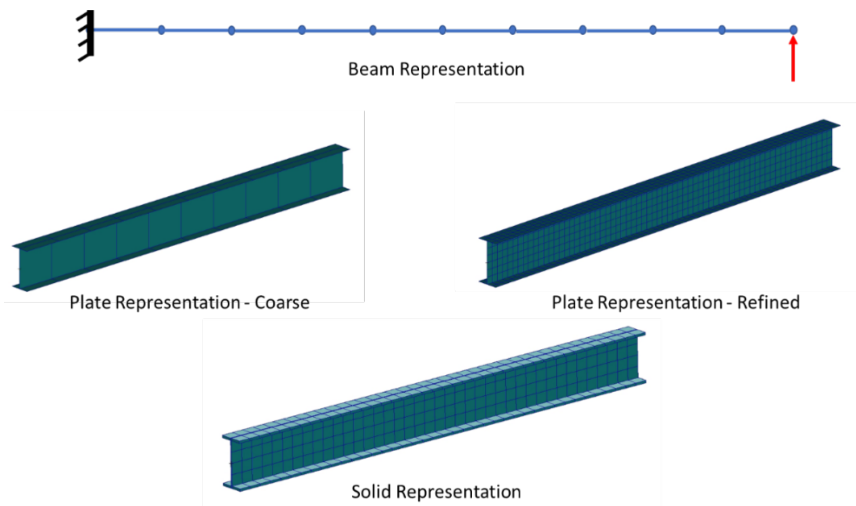


Fig. 4. Finite Element Beam Representations Used for Study

Table 2. Comparison of Cantilever Beam Results

Mesh Type	Tip Deflection	Normal Stress	Shear Stress
Classical Calculation	2.72 in	39.0 ksi	4.5 ksi
Bar/Beam	2.72 in	39.0 ksi	4.5 ksi
2D Plate - Coarse	2.67 in	33.5 ksi	1.4 ksi
2D Plate - Fine	2.67 in	36.0 ksi	4.5 ksi
3D Solid	2.70 in	41.1 ksi	4.6 ksi

Additionally, element selection and inherent interpolation assumptions can also lead to differences in results. Different programs have the ability to choose different types of element representations. For example, beam elements may have choices for full integration, reduced integration, inclusion of shear deformations, or other associated parameters. Likewise for shell elements, thin or thick shell formulations, reduced integration, full integration, and assumed strain formulations can all affect the output quantities of interest. Knowing the element formulation and output parameters associated with those formulations works in concert with the discretization strategy and ultimately must support the response quantity of interest desired from the analysis.

This type of exercise leads to the first set of observations for building confidence in analysis models via a building-block approach. Start with simple representations to understand global behavior. Simple representations can be obtained from classical closed form solutions or simple finite element representations such as beams. Beam formulae such as Mc/I, P/A, VQ/It, (where M = bending moment, V = shear force, P = axial tension/compression, t = material thickness, Q and I represent 1st and 2nd moments of area for the cross section) are very useful for evaluating whether results for overall global behavior make sense. Simple representations also are easier to tune and adjust as the design progresses to improve model performance.

Another way to build confidence is to use full 3D representations of simple problems with closed form solutions, such as the cantilever beam, to study mesh convergence and develop defendable modeling strategies that can be incorporated into more complex models (see Example 3). Overall, classical closed-form solutions are a powerful tool for both "back-of-the-envelope" sanity checks of global results and anchoring of larger FE models.

B. Example 2 - Use of Simplified Analysis Methods

Other methods such as axisymmetric analysis can be appropriate for evaluation of through-thickness effects in a structure if geometry and loading meet the axisymmetric assumptions. Pressure vessels where detailed stress levels in the wall are needed are good examples of areas where this type of simplified, and much less costly, analysis technique can be used to good effect.

An example using just such an approach is shown in Figure 5. In this case, a flight-like development test article metallic pressure vessel, where hardware components were machined below minimum-thickness tolerance, needed to be evaluated. An intermediate-fidelity 3D finite element model had been used to evaluate the overall stress state of the pressure vessel. Certain areas that had been machined too thin were predicted to experience gross yielding for the desired design pressure and the required proof test factor. To expedite reaching a disposition on whether to use the tank as manufactured or to scrap and start over, axisymmetric modeling was used. This allowed more detailed modeling to be used in local areas of interest where (1) localized yielding rationale needed to be developed, and (2) stresses were needed for fracture analysis. Local bending behaviors were verified first. Then, parametric studies for various combinations of de-rated design pressure and lowered proof test factor were performed. Based on the results from these studies, the analysis team recommended a de-rated design pressure combined with the original required proof test factor. This recommendation allowed the project to meet its objectives while still adhering to industry requirements without a waiver [16]. The axisymmetric modeling simplification was appropriate and adequate for the information required.

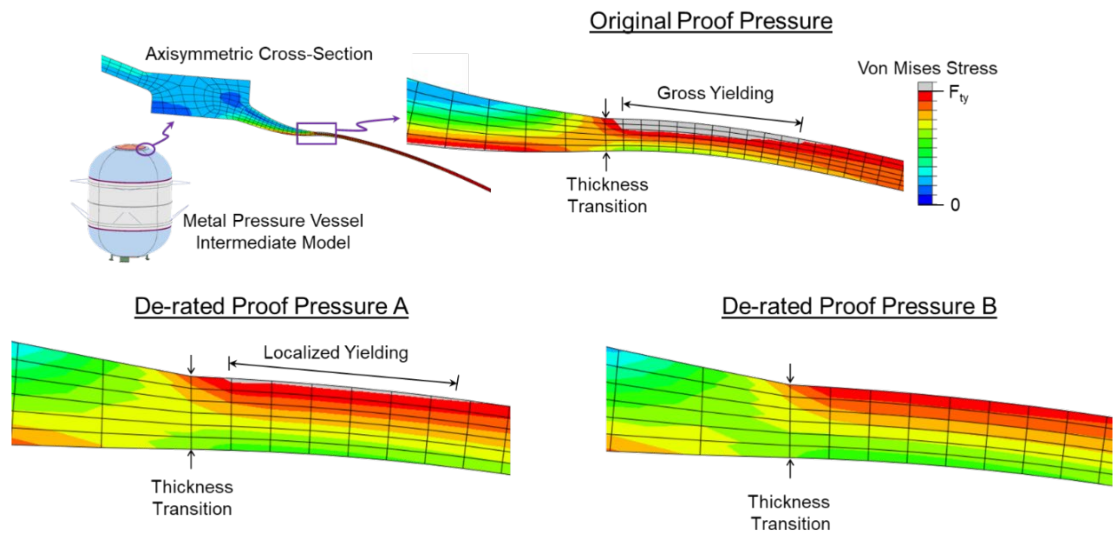


Fig. 5. Axisymmetric Modeling Example

C. Example 3 – Intermediate Fidelity 3D Modeling

Using modeling practices developed from exercises like those presented in Example 1, intermediate-fidelity models can be developed to (1) assess global response when the structure is subjected to more specific loads and boundary conditions [than those considered with hand calculations] and (2) begin assessing some local design details. The models are constructed in a way that builds off what was learned in the preceding simple assessments. There is no need to include all design features at this stage. For example, fastener holes, weld fillets, and in some cases, fillet radii, can all be omitted at this stage as none of these types of details add to the overall structural behavior of the part or assembly.

An example of this approach is presented in Figure 6 [16]. A flight-like development test article included a metallic pressure vessel supported by composite struts. Hand calculations for thin-walled cylinders subjected to internal pressure were used to determine basic structural dimensions and create 3D CAD geometry:

$\sigma_{hoop} = pr/t$
$\sigma_{axial} = pr/(2t)$
(where p is the internal pressure, r is the radius, and t is the thickness)

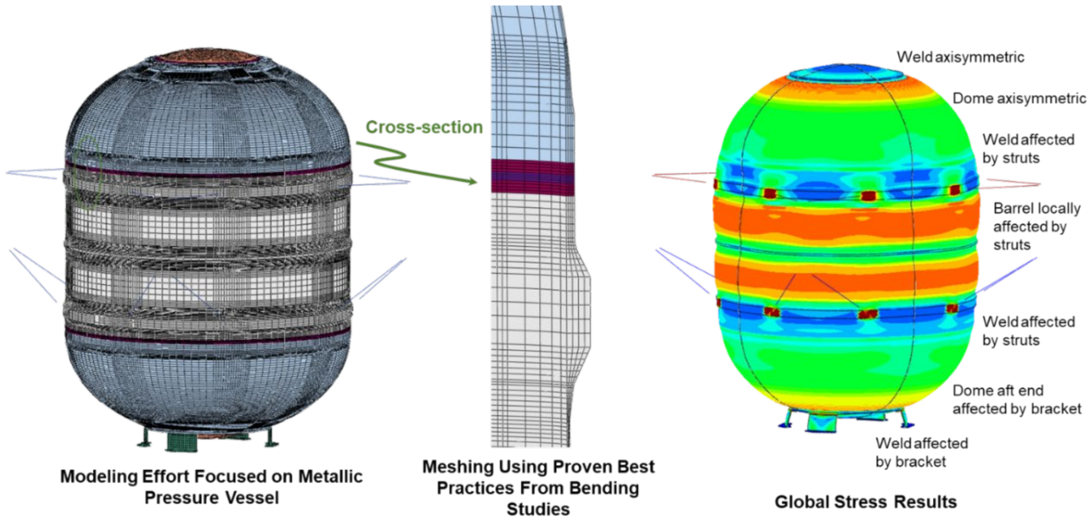


Fig. 6. Flight-like development test article metallic pressure vessel intermediate-fidelity 3D finite element modeling

An intermediate-fidelity model based on this 3D CAD geometry was created to assess global design details and confirm the credibility of the pressure vessel design. In this model, all fastener holes were not modeled, and the welds were idealized. Fillet radii were included. Because high-fidelity modeling of the composite struts was unnecessary to assess the metallic structure, they were simplified as beam elements with multipoint constraints.

The metallic structure was expected to experience bending in local regions when subjected to the internal pressure load. A history of cantilever beam modeling studies developed the analyst's personal, defendable best practices for modeling 3D structures subjected to bending when analyzed using the selected analysis software. These best practices were implemented in the construction of the intermediate-fidelity 3D model. Brick elements and through-the-thickness mesh refinement based on the cantilever beam studies were incorporated.

The simplicity of the model made it easier to assess the overall stress state of the metallic structure. Regions where the response due to the pressure load was unaffected by the other external loads were confirmed. This verified the "axisymmetric" regions of the structure and made it possible to use axisymmetric modeling for follow-on parametric studies. One region with a severe fillet radius was identified as needing modification. Because the stress model was relatively simple and well-constructed, it was easily modified so dimensional recommendations could be made and incorporated into the design for further assessment. Even though the geometry shown might have lent itself to axisymmetric modeling approaches, an intermediate approach using simplified defeatured geometry and controlled meshing with 3D elements was constructed. The constructed model was deemed an appropriate level of fidelity for the assessments that were needed from these analyses.

D. Example 4 - Large Scale Implementation

Use of the methods outlined above can be implemented into full structural design and verification models. A typical implementation of this sort was used to design/analyze/validate the spacecraft used in the Lunar Atmosphere Dust Environment Explorer (LADEE) Program in 2012-2013 [17].

The design concept used interchangeable composite sections (modules), octagonal in shape, to build up the spacecraft bus primary structure. The modules were honeycomb construction with carbon composite facesheets and aluminum core. Modules were connected at discrete locations, with L-type joints, embedded bushings, and bolts, to form the spacecraft. Internal honeycomb panels (cruciform section) were used to strengthen the structure and support internal instruments and hardware. Other structure and hardware elements were also connected via bushings and bolts with a total of 8 different bushing types being used throughout the structure. Figure 7 shows a graphical representation of the design.

Fig. 7. LADEE Spacecraft with Expanded View and Internal Structure

Initial sizing was developed via a combination of classical methods and other closed form solutions. For this effort, the Hypersizer software code [18], which implements data from handbooks and empirical testing to predict behavior of common aerospace structural components/configurations (stiffened plates, panels, etc.), was used to develop initial stiffness/thickness requirements. These initial results were then used to inform preliminary CAD representations of the structure based on this initial sizing. In this way, preliminary analysis was used to drive CAD geometry and not the other way around.

Once initial sizing was completed, a more detailed sub-component model of the structure was developed. This model included behaviors of complex aspects of the design (bushing and corner joints), which were represented as spring/bar elements, as shown in Figure 8.

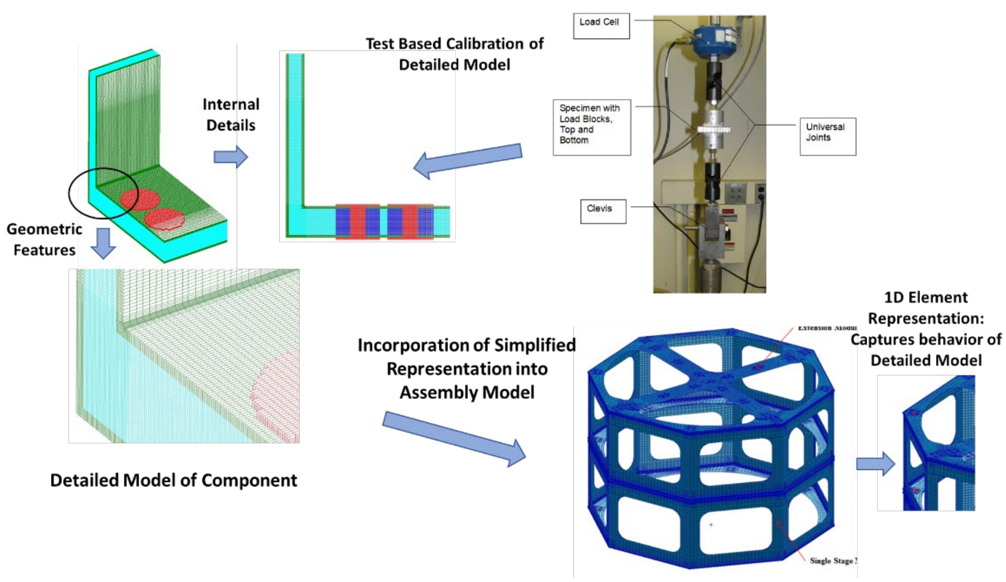


Fig. 8. Incorporation of Test-Based Behavior and Detailed Modeling Results into Upper-Level Models as Simplified Representations

Knowledge from the preliminary development was used to create a full assembly model of the spacecraft. Figure 9 shows an overview of this final model. The spacecraft assembly model, which included simplified representations mentioned above, was used to interrogate all required load cases and provide margin information to ultimately qualify the design.

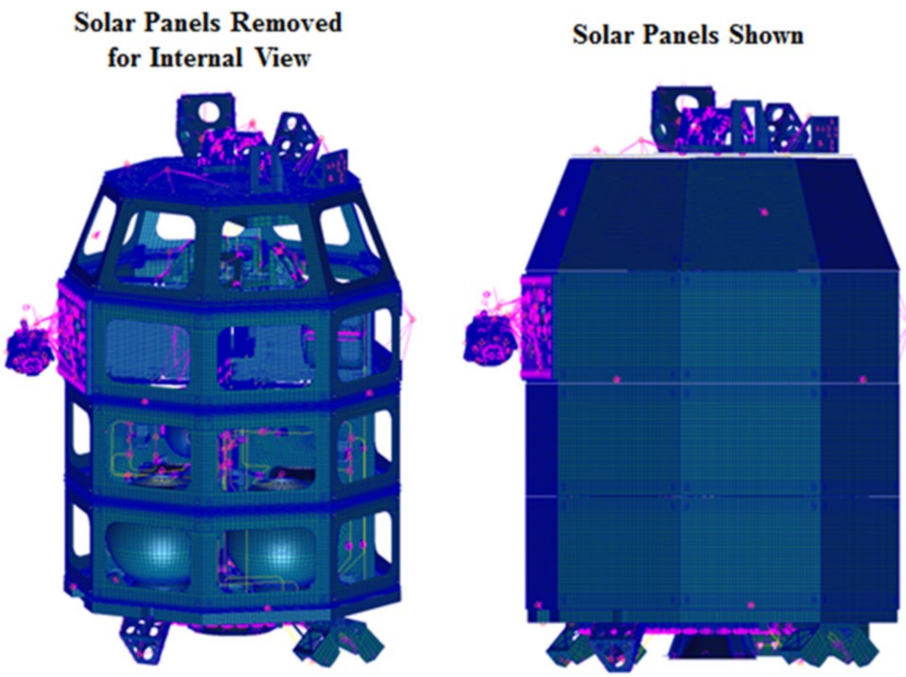


Fig. 9. LADEE Master Verification Model

To summarize, these examples of the analysis building-block process illustrate some of the following concepts:

- Use hand calculations or closed form solutions to get basic structure in the correct ballpark to meet functional requirements such as beam or basic pressure shell equations.
  MC/I, P/A, VQ/It, pr/t, pr/2t, etc.
- Use results of preliminary calculations to develop basic preliminary CAD models *before* detailed (stress) models are needed or required.
- Use simple models to gain understanding of modeling methods, behavior of elements, assumptions, software peculiarities, etc., to develop modeling practices that can be justified in more complex, higher level models. (See Example 1)
- Maintain simple representations where fidelity is already appropriate. A section of structure that behaves like a beam can be represented as a beam. It is not necessary to add extra complexity to an analysis. More complex meshes are harder to interrogate and validate (e.g., to extract a bending moment from a 3D model requires adding and summing contributions at individual nodes, whereas a beam or plate element gives this information directly).
- Use simplified analysis techniques, such as axisymmetric modeling or symmetric/antisymmetric cuts, where appropriate. These can be effective in evaluation of certain types of structural configurations. (see Example 2)
- Use simpler models to establish best practices for more detailed modeling. This aids in the creation of intermediate-fidelity models that are appropriate for obtaining global and some local response but are still easily modifiable. (see Example 3)

- When some local behavior is complex, detailed local models may be used to develop characteristics which can be implemented into springs or beams used in a large assembly model. These simplier representations can be used to determine overall structural behavior. Loads from the assembly can be transferred back to the local model if local stress behavior is needed. (see Example 4)

IV. Virtual Testing and Hybrid Simulation

While what has been presented so far outlines a traditional building-block approach, some new ideas and technologies are appearing on the horizon. Virtual Testing and Hybrid Simulations are two such concepts. Some ideas connected to these new technologies are presented in this section.

Meeting regulatory requirements and customer expectations while maximizing profitability is a delicate balance for manufacturers. Over the last few decades, advances in computer technology and continuously improving analytical tools with multi-physics and multi-scale analysis capabilities have opened new doors for layout, analysis, and optimization of new designs. Thousands of load cases with simultaneous mechanical, thermal, and fluids interactions can be solved in a relatively short time. Material and structural non-linearities and complex boundary conditions can be more efficiently addressed than in the past and even stretched to the limits of design parameters. Probabilistic analysis methods can be applied, varying numerous parameters to bound the solutions and quantify uncertainties. Achieving this kind of capability via a conventional test-based building-block approach is usually complex and costly. A new solution that is being explored for meeting safety and cost efficiency is to exercise a hybrid virtual/physical certification approach.

Virtual testing is a method that simulates lab testing using analysis software, while hybrid simulation is an approach of analyzing analytical models of physical structures integrated with models of test processes combined with realistic loading conditions that includes test hardware coupling. Both methods have the potential to reduce time and cost. Virtual testing can be a valuable tool in predicting test outcome and building confidence going into an expensive test program. It can predict stress distribution, resonant frequency, buckling load, and fatigue life under realistic loading. Advanced Composites and Additive Manufacturing structures are great candidates for a hybrid test-simulation approach where the number of physical tests can be greatly reduced. Hybrid simulation combines the lab testing with numerical analysis to explore the benefits of both methodologies. You et. al. [19] present an excellent discussion on this topic with examples.

Major aerospace manufacturers across the globe are already working to develop guidelines towards uniform virtual testing and hybrid simulation methods for certification of new designs. Virtual testing provides a great advantage since it can occur during an earlier development stage, long before components are manufactured, and physical testing can begin. Of course, one major caveat is that these models must be validated by a competent physical test program before they are used to expand the analysis envelope. With relatively accurate predictive ability of the performance of physical test systems, virtual testing has the potential to be used as pre-test to physical tests, optimize various test parameters, and perform partial or localized simulations. As a result, both analytical models and physical test programs can be simplified and optimized. This approach also opens a window for reevaluation of test-based factors of safety for streamlining certification programs and identifying potential weight savings.

V. Concluding Remarks

Building-Block approaches are commonly employed in aircraft and space vehicle development and are known to effectively reduce technical risk and development cost. The complexities of lightweight, built-up structures led the industry to develop a building-block approach. The building-block approaches rely on analyses and tests of elements and subcomponents to establish the effects of local details and internal load paths on structural behavior. The building-block approach also addresses manufacturing scale-up issues. Application of building-block approaches in analysis provides a good road map for systematically analyzing a structural design. Insight is gained on appropriate mesh density and element selection, for example. Insight is also gained into performance aspects of the model, validation of the model form, and interactions among various parts and regions of the structure. Simplified modeling techniques, such as the ones outlined in this paper, can be used to gain this understanding of behavior and validation of modeling assumptions.

As demonstrated in this paper, building-block approaches need not lead to the development of full 3D representations to capture the desired behavior. Simpler representations such as 2D meshing, defeatured geometry, usage of springs/bars to incorporate the stiffness and load transfer aspect of joints, and axisymmetric representations can all be used effectively and constitute an appropriate level of fidelity when used correctly. High-fidelity answers can be achieved even from simple representations.

The development of a structural model should start with the behavior that needs to be captured in mind. The more complex a representation of an area, the more difficult it can become to extract relevant data. For example, if shears, moments, or axial forces at specific locations are the primary analysis quantities of interest, some sort of beam representation might be more appropriate if it can capture the proper geometry.

Modeling, at any level, should not be more complicated than it needs to be. Use the building-block methods to identify and anticipate the important global structural behaviors that need to be captured first. Then plan subsequent, and perhaps more detailed, analyses after areas and values of significant interest have been determined.

Finally, development and acceptance of model-based certification and test/analysis hybrid simulation of complex structures is on the horizon, with many large aerospace companies investing in these methodologies. Understanding of complex simulations, by building up of confidence that starts with simpler representations and works toward the more complex, should be an important part of these certification efforts.

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