THE ROLE OF OPTIMIZATION IN COMPONENT STRUCTURAL DESIGN: APPLICATION TO THE F-35 JOINT STRIKE FIGHTER

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Abstract

During design and development of the F-35 Joint Strike Fighter (JSF) the program has maintained a focus on weight minimization that has continued through detail component design. The program has applied structural topology, shape, and sizing optimization tools and methods to optimize load paths and sizing of structural components to realize weight savings. These tools and methods have been applied to reduce weight and improve design decisions on compact fittings, doors, and shell components. Parts with sufficient design freedom benefited substantially from methodical optimization. This paper outlines the optimization process employed on F-35 and its impact, providing several examples to illustrate process details.

1 Introduction

The F-35 Joint Strike Fighter (JSF) faced a substantial weight challenge during the design phase of the Short Take-off and Vertical Landing (STOVL) version. The JSF Program Office (JPO), Lockheed Martin, and JSF partner companies aggressively pursued weight reduction initiatives to bring the design within weight targets because decisions made during aircraft development will be significant drivers of cost and performance through the life cycle of the aircraft. Major weight reduction trade studies executed during 2004 and 2005 addressed every aspect of the aircraft, including structural arrangement, materials, and requirements. The F-35 program maintained the weight minimization focus during design of the Conventional Take-off and Landing (CTOL) and Carrier (CV) versions of the aircraft.

Pursuit of weight reduction has continued through detail component design, where substantial effort has been made through rigorous structural analysis and optimization to understand load paths and weight-driving design parameters in each component. As part of this effort, the F-35 Program instituted application of structural optimization tools and methods to optimize load paths and sizing of structural detail parts to realize weight savings. Taylor, et al. provided an overview of this optimization effort on the STOVL version of F-35 [1], providing examples limited primarily to compact fittings.

This paper discusses the expanded role that finite element based structural optimization tools have filled in the design of broader classes of components on the F-35 Joint Strike Fighter, discussing the value, challenges, and opportunities for improvement that have been discovered through their application. This paper focuses on the issues involved in implementing optimization tools and methods in a production aircraft development environment. First, the paper outlines issues in realizing the potential benefits of optimization and the author's view of how optimization fits into the structural design process. Next, the paper discusses the application of optimization tools and methods to F-35 structural components, providing specific examples to illustrate the processes used. Finally, the paper examines the downstream impact of the optimization process.

2 Realizing the Potential of Optimization

While formal mathematical programming methods have existed for greater than a century and computational implementations of these methods date to 1960 [2], the practical application of optimization methods to reduce weight in real aircraft development has only recently begun to take hold.

In 1981, Ashley [3] surveyed literature, friends, colleagues, and specialists and found only limited examples where optimization had been applied to work that had been incorporated in an actual flight vehicle. The field of multidisciplinary design optimization has attracted much research interest and found success in real applications. For example, the X-29 used an aeroelastic tailored graphite epoxy forward swept wing, designed by advanced analytical and optimization tools [4] [5]. Recent years have seen development of tools for multidisciplinary configuration optimization [6].

Successful aeronautical structural optimization application has been predominately sizing optimization [7]. For example, Engelstad, et al. [8] compared a gradient-based approach to the Automated Sequential Sizing System (AS3), a Lockheed Martin tool for fully-stressed design, which was used in the redesign of a horizontal stabilizer. Topology and shape optimization have only recently seen application [9].

While progress is being made, the potential value to be gained from broad-based application of optimization tools and methods in production development processes is still not being realized. The major barriers to unlocking the value of optimization are now cultural and managerial in nature. Successful optimization in a production development environment, or value-added optimization, requires effective and efficient man-machine interaction, effective and efficient structural analyst-designer interaction, and process organization that promotes successful optimization. First, effective man-machine interaction requires an effective and efficient preprocessor that can be guided by good engineering judgment to bound the problem and make it tractable, ensuring all constraints are either explicitly or implicitly addressed. Omission or poor formulation of even one constraint leads to undesirable effects and dismissal of the results as irrelevant. Second, the structural analyst and the designer must interact effectively with the optimization toolset to bridge their skills and tools, either through tight optimization interaction between the designer and structural analyst or development of individuals with more integrated skills and knowledge. Finally, the window of value-added opportunity in the structural design process is narrow. Optimization must be planned for at the right time in the development process or else it will not add value, will conflict with structural analysis work, duplicate effort, and will be resisted by all.

3 Optimization in the Structural Design Process

Realization of the potential value of optimization requires an understanding of the design process and where optimization fits in this process. This section presents a simplified model of the aircraft structural design process and a brief overview of the optimization techniques available.

3.1 Structural Design Process

For the purposes of this paper, the airframe structural design process can be represented in a simplified form by three stages, as shown in Figure 1. At the upstream system level, layout and design entails determination of global structural configuration, preliminary sizing, and internal loads, all with a minimum level of detail. During downstream component final structural analysis, every part must be fully defined geometrically and checked at critical locations against criteria for static strength, stability, stiffness, durability and damage tolerance (DaDT), and any significant environmental or special considerations. In the middle is a stage where the detail component design is matured to arrive at a full geometric definition. During this phase, it is expected that

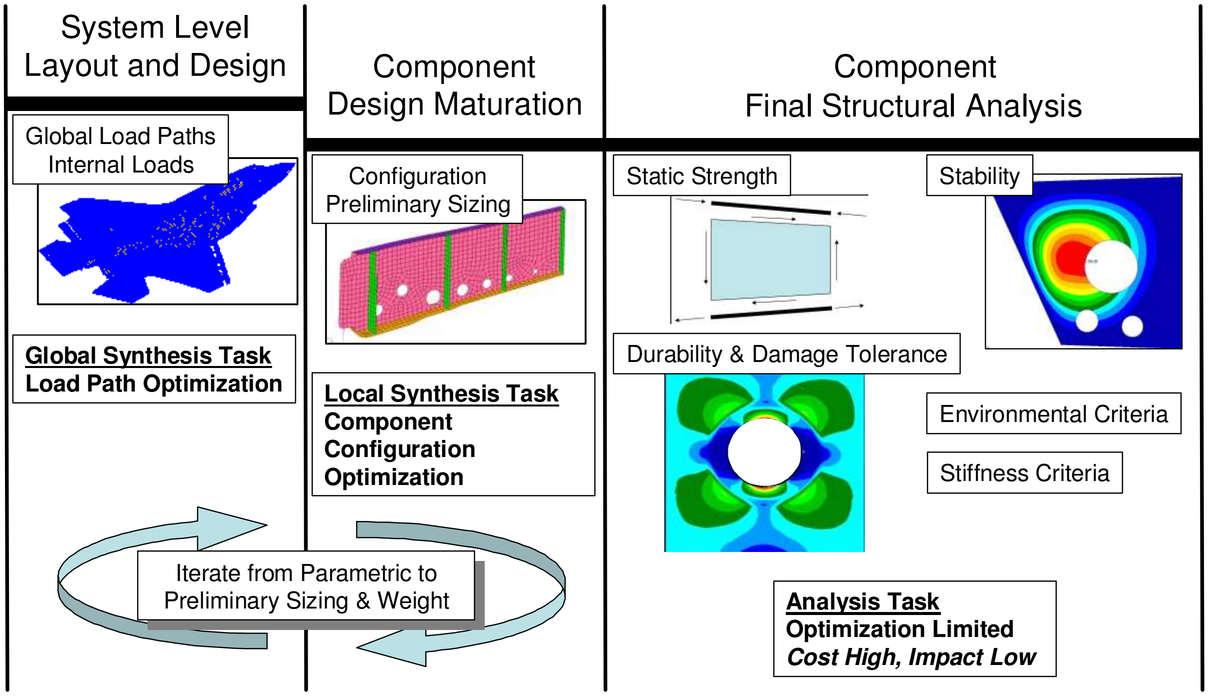

Figure 1: Structural Design Process Stages

the final part configuration is determined and preliminarily sized, although the sizing will be adjusted during component final structural analysis. If a required change to the configuration is discovered later during the component final structural analysis, it typically requires a lengthy iteration and can impact surrounding structure and systems.

Optimization is inherently a synthesis activity and, ideally, optimization methods should be applied during the component design maturation phase when part synthesis occurs. During this phase, preliminary loads are available, critical constraints can be addressed while simplifying for detail driven criteria that can be addressed downstream (e.g. fillet radii driven by DaDT). Topology, shape, and sizing optimization methods can generate component configurations that have low risk of future configuration change, as required to complete the component design maturation phase. These optimization methods cannot of themselves be the final structural analysis because they include simplifying assumptions and are driven by finite element results, which, while frequently meaningful to the process, are not directly used for writing final margins [10]. Additionally, the inclusion of constraints ordinarily not addressed until final structural analysis means that the sizing, and consequently the weight estimate, produced through the optimization process is of higher fidelity and will reduce the risk of expensive downstream iterations. The final component structural analysis that follows is, therefore, more likely to be a verification process rather than, as is typical, an iterative redesign process. This reduction of late cycle iterations yields reduced cycle time during component final structural analysis.

Optimization applied during the final component structural analysis phase may still save weight but, because optimization is a synthesis activity, it essentially recreates work already completed during the component design maturation phase. Consequently, much of the potential for cycle time reduction evaporates and organizational resistance to late cycle design changes impedes acceptance of potentially lighter weight components.

3.2 Optimization Techniques

Three different optimization techniques, topology, shape, and sizing, have been applied to JSF parts and found to be effective, each in its own way. Figure 2 shows notional examples of these three techniques. Topology optimization, shown in Box a) of Figure 2, seeks to determine the best arrangement of a limited volume of structural material within a given spatial domain to maximize some performance metric, typically stiffness. The topology optimization employed on JSF uses the density method [11] [12], incorporated within commercial finite element software tools, wherein element density is treated as a design variable for each designable finite element. Through an iterative procedure, regions with high strain energy are allocated greater densities and regions with low strain energy have their densities reduced, thereby producing variable density results within the structural domain that indicate preferred structural layout.

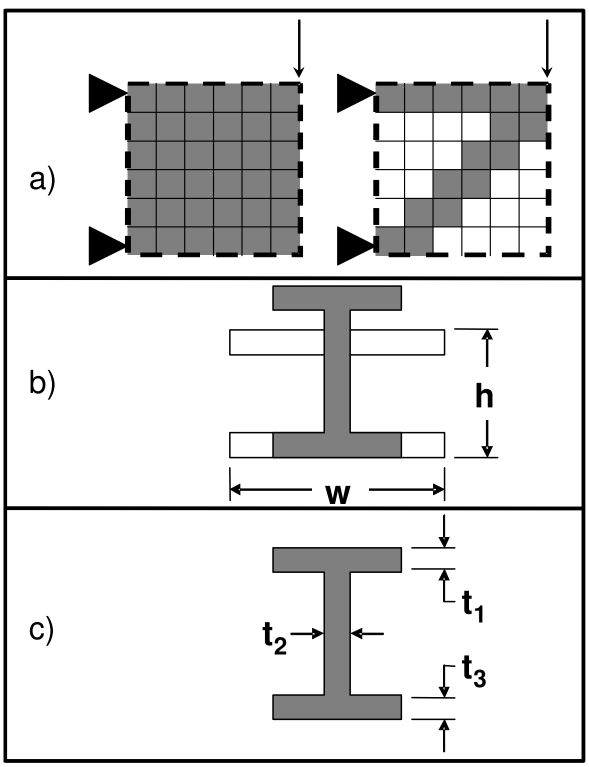

Figure 2: Optimization Techniques

Shape and Size optimization methods used in this work employ gradient-based mathematical programming algorithms [13] [14] incorporated within commercial finite element software tools. Shape optimization, shown in Box b) of Figure 2, adjusts boundary definitions in order to improve some performance metric, which is typically weight in structural optimization. The method employed on JSF involves definition of shape basis vectors by means of mesh morphing in the finite element preprocessor. These shape basis vectors are then used as design variables within the optimization algorithm.

Size optimization, shown in Box c) of Figure 2, adjusts entries on finite element property cards to improve the weight performance metric. In this work, the thickness entry is primarily used to define design variables and reduce weight through the gradient-based algorithm. Because many aeronautical structures consist of built up shell configurations, this type of optimization has been most easily applied and has received the greatest application in the industry.

The general process of optimization followed on JSF involves the application of each of these three optimization techniques. Typically, the process begins with topology optimization to determine the load paths and configure the structure along these load paths. In topology optimization the standard objective is to minimize compliance while constraining allowable volume within a package space, which bounds the volume usable for structural material. This optimization technique typically does not address strength and stability constraints so no sizing is inferred, only relative stiffness trends that guide efficient material distribution. Subsequently, shape and sizing optimization are applied to adjust geometry and address strength and stability. Various iterations and combinations of these techniques have been used to address different types of parts in different environments and stages of maturity.

4 Optimization of F-35 Structural Components

The optimization techniques described previously have been applied to numerous parts on JSF. Applications have generally included compact fittings, doors, and carveouts of shell structures.

The key to enabling the use of optimization has been the availability of a preprocessing tool to reduce the overhead associated with optimization model setup. Topology, shape, and sizing optimization of compact fittings on JSF has primarily used the Altair HyperWorks tool suite, developed by Altair Engineering Inc. Within this suite, the HyperMesh preprocessor provides efficient preprocessing facilities for the setup of optimization models and the OptiStruct linear finite element solver includes algorithms for topology, shape, and size optimization. Additionally, some sizing optimization has been executed using MSC NASTRAN.

4.1 Compact Fittings

The initial class of parts targeted for optimization was compact fittings, such as attachment brackets and gooseneck door hinges. Compact fittings present a straightforward application of optimization because the effects are localized, the package space is tight, and the loads and boundary conditions are relatively simple. Consequently, the optimization procedure is straightforward and credible results can be obtained with reasonable effort.

The general optimization process for compact fittings begins with solid topology optimization followed by shell size and shape optimization. Compact fittings benefit most from the application of topology optimization to study load paths within a compact structural domain. Use of topology optimization to determine the stiffest configuration results in more efficient use of material and a lighter weight part. Consequently, topology optimization alone, without subsequent shape and sizing optimization, has sometimes been used to quickly discover opportunities for improving the structural efficiency of a compact fitting.

Typically, however, topology optimization is followed by size and shape optimization to address strength, deflection, stability, and geometric constraints directly. These models usually employ a shell idealization even though this idealization is not strictly valid in some areas of compact fittings. The efficiency in executing a shell optimization model justifies the omission of detail stress results in fillet radii and material distribution inaccuracies. These details must, however, be addressed downstream from the optimization model.

Figure 3 illustrates this process as applied to a door hinge. The hinges were optimized within a larger model, shown in Box 1, that

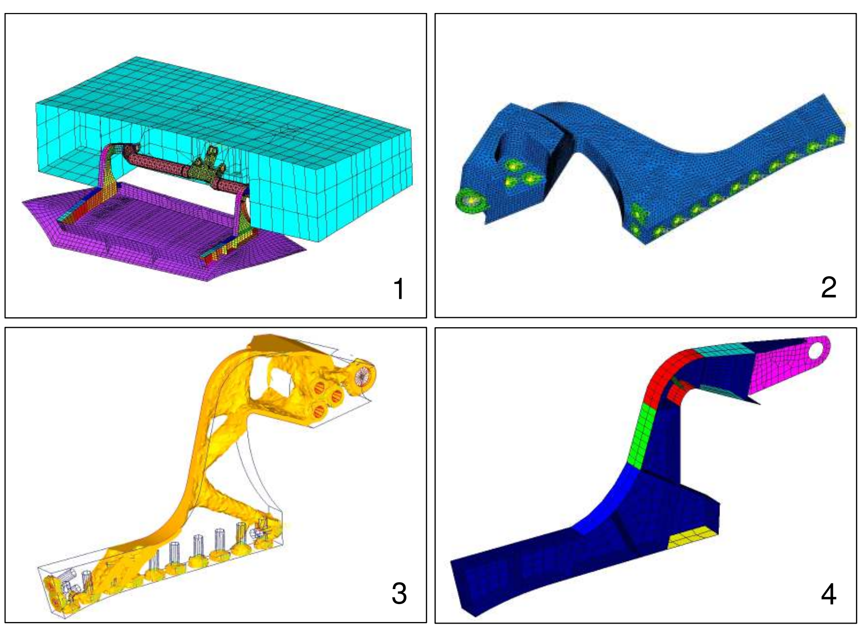

Figure 3: Compact Fitting Optimization

defines the loading and deflection constraint that drives the hinge design. The hinge package space, shown in Box 2, was then defined based on neighboring parts and stay out zones. This entire package space was meshed with solid elements and topology optimization was then executed as shown in Box 3. Topology optimization results suggested stiffener locations, which were defined in a shell finite element model, as shown in Box 4. This model had design variables for web, flange, and stiffener thicknesses, which were optimized for a minimum weight part to meet the deflection constraint defined in the model of Box 1.

Many F-35 compact fittings have been optimized through variations on this process. Additional examples and results are discussed by Taylor et al. [1].

4.2 Doors

The next application of optimization methods on F-35 has been to doors. With these structures optimization driven effects are still localized, like compact fittings, but the structures are larger, multi-part components with additional complexity. Optimization of these components has typically followed a two-level approach where the door is first optimized followed by the hinges and any other attachments, overall door structural performance being driven by the effectiveness of the door and hinges acting together.

Doors are typically loaded by external pressures and actuator loads. Their design is frequently driven by stiffness, with a deflection requirement sensitive to the door stiffening concept (honeycomb stiffened composite vs. integral metallic stiffeners) and configuration as well as hinge stiffness. With a metallic door, topology optimization can sometimes provide useful insight for stiffener layout. With a composite door, facesheet ply thickness and composition can be optimized (smeared or discrete plies) over max depth honeycomb core, which can be meshed with solid elements if transverse shear is significant. The subsequent hinge optimization follows the compact fitting optimization process described in the previous section using a combined door and hinge model to determine overall door performance.

Two examples of door optimization are presented here. The first example, shown in Figure 4 Box 1, shows a high aspect ratio door with limited package space for stiffening. Topology optimization, shown in Box 2, suggested a mostly longitudinal stiffening pattern, as expected, with some angled stiffeners at the ends. The interpreted stiffener arrangement, shown in Box 3, was modeled in a shell finite element model with design variables defined for stiffener thicknesses. The door hinges would be optimized similar to the

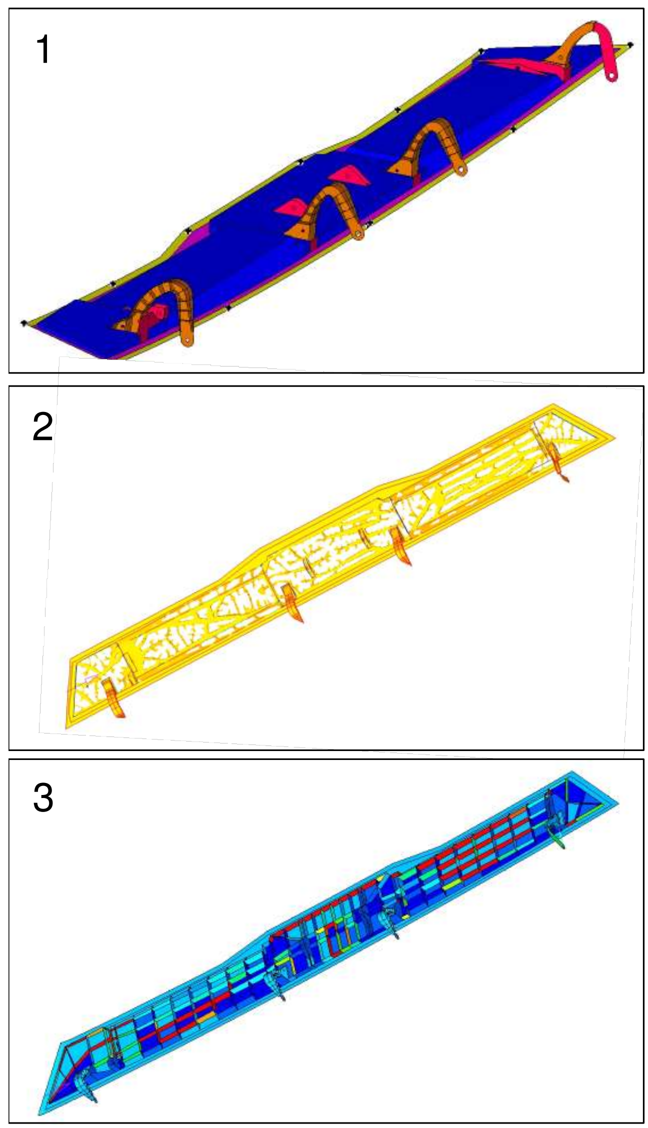

Figure 4: Door Optimization—Example 1

example in the previous section, down stream of the door itself but driven by the same door stiffness constraints. Optimization of the hinges has not been executed as of this writing.

This optimization exercise quickly generated a data point showing the door would not meet design objectives given constraints placed on it by surrounding structure. Because the optimization provided this information early, some reconfiguration of surrounding structure was pursued to alleviate some of these constraints.

The second example, a more compact door with integrated hinges, shown in Figure 5, made more direct use of topology optimization. The package space, shown in Box 1, was first defined as constrained by neighboring parts and stay out zones. The topology results, shown in Box 2, suggested a stiffener pattern, which was defined and meshed, as shown in Box 3. Sizing of the door, stiffeners, and hinges to meet deflection constraints was accomplished simultaneously with thickness design variables defined on each of these features. The result of this sizing is shown in Box 4.

As illustrated by these examples, sizing optimization efforts on F-35 doors have generated valuable information to guide preliminary design and configuration decisions. On the other hand, the value of topology optimization on door components depends on the nature of the door geometry and package space. A high aspect ratio door needs longitudinal stiffeners, which was known a priori. Topology optimization of a low aspect ratio door can yield greater benefits as the optimal stiffener pattern may be less intuitive.

4.3 Shell Structure Carveouts

Integrated, built-up shell structure, including single and multi-part components, has been optimized on F-35. Optimization of such models presents a host of challenges that impact the effort required and the conclusiveness of the optimization results.

These challenges include the presence of both external applied and internal freebody loads, effective incorporation of buckling constraints, inclusion of boundary stiffnesses, and preservation of global load paths. First, because shell parts are typically analyzed as a

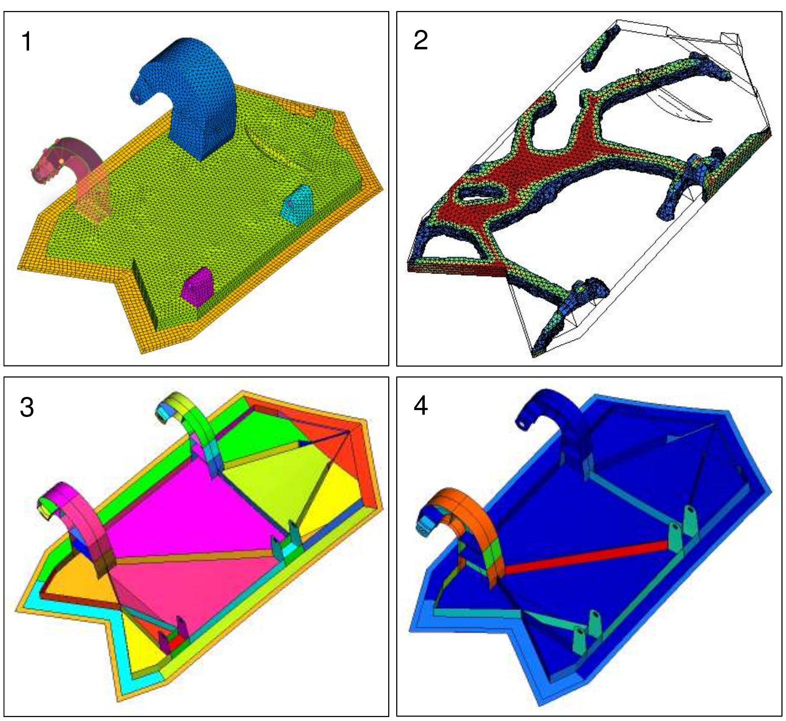

Figure 5: Door Optimization—Example 2

carveout from an integrated structure, freebody loads are extracted from the global loads finite element model for specific load cases in equilibrium. Any change in model geometry driven by the optimizer unbalances the load case, often necessitating the use of inertia relief to artificially balance the loads. Use of inertia relief, however, precludes the use of buckling constraints, which are primary drivers of the built-up shell structure that comprises the bulk of an airframe. The hierarchical approach suggested by Schramm, et al. [15], whereby buckling is checked after optimization, is the necessary, but not necessarily optimal, workaround process. Additionally, optimization using breakout shell models has the potential to change part stiffnesses sufficient to alter load paths and invalidate the global loads model. Boundary stiffness and forces must be checked and either constrained or otherwise accounted for during any optimization using a local breakout model. Finally, an integrated shell part is sensitive to the stiffness of the surrounding structure, which, consequently, must be accounted for in the optimization model. This structure can be accounted for either by modeling it directly or through the use of static condensation for direct matrix entry [16].

The primary optimization tool employed on shell parts has been sizing optimization to determine flange, web, and stiffener thicknesses. Additionally, some shape optimization has been used for minor geometric adjustments. Shell parts are typically driven by static strength, DaDT, panel stability, flange crippling, and stiffness constraints, all of which can be addressed in shape and size optimization.

Topology optimization could be useful to aid structural layout but has not been applied early enough to impact such decisions on F-35. On the part level, topology optimization of shell structure is generally less fruitful because the resulting load paths are quite sensitive to the predetermined surrounding stiffnesses and geometric connections. Additionally, topology optimization algorithms have difficulty addressing buckling constraints [15], [17]. Topology optimization thus produces little useful information on most individual shell parts. Free size optimization [18] may ultimately prove to be more useful in this capacity.

Figure 6 shows an example of a sizeable carveout shell model that has been optimized on F-35. This model consisted of a region of structure in a highly redundant stiffness driven problem. Loads consisted of external applied loads within the optimization region as well as freebody loads on the section boundaries. The overall modeling effort involved finite element mesh updates, panel effectivity calculations, optimization model configuration and execution, and margin calculations. Engineers constructed and executed an optimization model with 260 design variables to determine trends and weight deltas for 30 structural configurations, studying the effects of panels, panel effectivities, bulkhead depths, bulkhead materials, and lug pin sizes.

During a 4 week span engineers were able generate data to make an informed and balanced structural configuration decision. Without this modeling effort, configuration decisions would have been based on speculation and broad assumptions with the high risk of added weight. Instead, these weight deltas provided a factual basis for management configuration decisions to balance cost, weight, and maintainability.

Because this study was preliminary in nature several of the carveout optimization issues highlighted earlier did not apply. Two issues in particular were addressed. First, the design region was surrounded by a substantial buffer of surrounding structure, shown by the region in blue in Figure 6, to include the effects of boundary stiffnesses. Second, the applied external loads were balanced by internal freebody loads on the model boundaries. During the optimization process SPC forces were monitored to ensure the loads remained balanced. Because sufficient structure bounding the design region was included, freebody loads remained sufficiently balanced as the optimizer adjusted thicknesses. Results were verified after optimization by solution of the full aircraft finite element model.

Boundary stiffness and internal loading could be addressed in a more sophisticated static

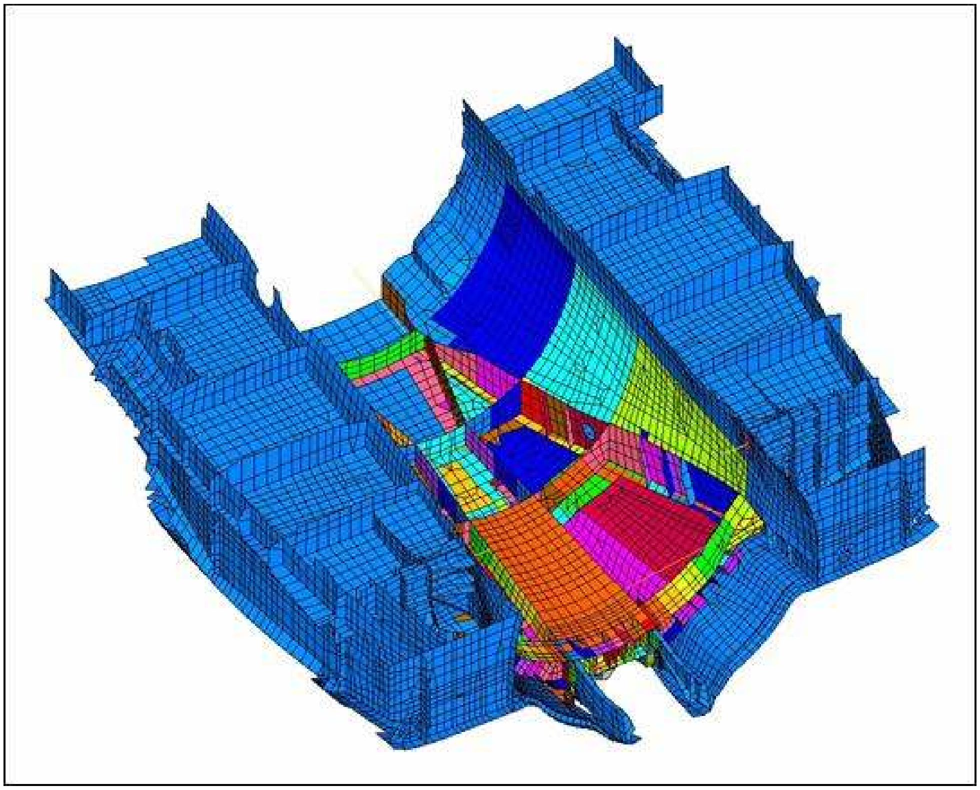

Figure 6: Carveout Optimization

condensation procedure, which is being pursued in current and future efforts. This example, however, had a large number of boundary nodes, producing a cumbersome DMIG that was deemed unnecessary when freebody loads proved sufficiently accurate.

5 The Role of Optimization in Structural Design

Taylor et al. [1] described the impact of optimization on final structure. They highlighted that optimization can not be the final structural analysis for a component; rather, it should aim to provide a robust preliminary design. Because final detail structural analysis must follow in order to determine all critical margins of safety, component optimization must have the objective to improve the structural analyst's ability to execute final detail structural analysis, achieving minimum weight at minimum cost and schedule. Optimization should ensure that final detail structural analysis is primarily a verification process, checking all the boxes, as opposed to the start of late cycle configuration changes that typically occur when some aspect of the part is found to not satisfy requirements.

Taylor et al. further discussed the need to apply reasonable simplifying assumptions to balance optimization effort with result fidelity. These simplifying assumptions include, for example, use of finite element results to size features (which are typically sized by forces and moments resolved on section cuts) and exclusion of local details driven by DaDT that do not impact gross area sizing. Optimization results will be questionable or even dismissed if simplifying assumptions are too great. If no simplifying assumptions are made, the optimization problem will usually be too time consuming or even intractable.

In addition to these observations, it should be noted that optimization provides a powerful tool to support design decisions. The examples presented in this paper all faced significant design challenges where structural layout had to be balanced against requirements for mechanism kinematics, producibility, maintainability, and other design rules. All of these considerations impacted component weight. Without optimization, only one or two structural configurations could have been studied within the time available. Optimization tools provided the means to generate meaningful weight comparisons for many configurations within a time span sufficient to support design decisions. Consequently, the resulting decisions more effectively balanced the full spectrum of requirements with the weight penalty for each consideration. This conclusion supports the assertions of Taylor, et al. [19] and Taylor and Weisshaar [20] that optimized structure improves structural information fidelity and puts the structural analysis discipline on a more equal basis with other design disciplines, thereby improving design decisions and the structural design process.

6 Conclusion

The F-35 JSF program has found weight savings, expedited the maturation of numerous structural components, and made high-quality design decisions by applying finite element-based structural optimization tools. These tools have been applied to compact fittings, doors, and more integrated shell components. While experienced engineers performing standard structural analysis and design iterations may get to minimum weight over time, optimization is a tool to get there faster if an effective optimization toolset can be employed at the appropriate phase of the development process. Furthermore, optimization can provide high-quality structural information to support fact-based design decisions balanced against all requirements.

While optimization is a multifaceted tool for education, design, weight-savings, time savings, cost-savings, and requirements management, all of these benefits are only potential and realization of this potential depends greatly on how the tool is applied. If optimization's potential value is to be realized, aircraft structural engineers and tool developers must work together to overcome the challenges that remain. Aircraft structural engineers must work to overcome the separation of design and structural analysis disciplines and define methods for applying optimization appropriately within the production development environment. Tool developers must help to develop methods to further integrate optimization methods into the process of aircraft structural design and analysis, addressing the complex nature of aircraft loads and constraints and reducing the overhead associated with execution of optimization methods.

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8 References

[1] Taylor R, Thomas J, MacKaron N, Riley S, and Lajczok M. Detail part optimization on the F-35 Joint Strike Fighter. *Proceedings 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Newport, Rhode Island, 2006.

[2] Schmit L. Structural design by systematic synthesis. *Proceedings ASCE 2nd Conference on Electronic Computation*, Pittsburgh, PA, pp.105-132, 1960.

[3] Ashley H. On making things best—aeronautical uses of optimization. *Journal of Aircraft*, Vol. 19, No. 1, pp. 5-28, 1982.

[4] Lerner E. The application of practical optimization techniques in the preliminary structural design of a forward-swept wing. *Collected Papers of the Second International Symposium on Aeroelasticity and Structural Dynamics*, DGLR Bericht 85-02, Aachen, West Germany, pp. 381-393, 1985.

[5] Shirk M, Hertz T., and Weisshaar T. Aeroelastic tailoring - theory, practice, and promise. *Journal of Aircraft* Vol. 23, No.1, pp. 6-18, 1986.

[6] Hunten K, and Blair M. The application of the MISTC framework to structural design optimization.

Proceedings 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Austin, Texas, 2005.

[7] Schmit L. Structural synthesis—its genesis and development. *AIAA Journal*, Vol. 19, No. 10, pp. 1249-1263, 1982.

[8] Engelstad S, Barker D, and Ellsworth C. Optimization Strategies for [a] Horizontal Stabilator. *Proceedings 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Norfolk, VA, 2003.

[9] Krog L., Tucker A., and Rollema G. Application of topology, sizing, and shape optimization methods to optimal design of aircraft components. *Proceedings 3rd Altair UK HyperWorks Users Conference*, 2003.

[10] Vaughan R, and Daniel M. The correct use of finite element models for stress analysis of aircraft, *Proceedings American Helicopter Society 60th Annual Forum*, Baltimore, MD, 2004.

[11] Bendsoe M. Optimal shape design as a material distribution problem. *Structural and Multidisciplinary Optimization*, Vol. 1, No. 4, pp. 193-202, 1989.

[12] Bendsoe M, and Sigmund O. *Topology optimization—theory, method, and applications*, Springer, Berlin, 2003.

[13] Vanderplaats G. *Numerical optimization techniques for engineering design: with applications*, 3rd Edition, Vanderplaats Research and Development, Inc., Colorado Springs, CO, 1999.

[14] Fleury C. Mathematical programming methods for constrained optimization: dual methods. Chapter 3 of *Structural Optimization—Status and Promise* (Kamat M, ed.), American Institute of Aeronautics and Astronautics, 1993.

[15] Schramm U, Zhou M, Tang P, and Harte C. Topology layout of structural designs and buckling. *Proceedings 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Albany, New York, 2004.

[16] Cook R, Malkus D, and Plesha M. *Concepts and applications of finite element analysis*, Wiley, New York, 1989.

[17] Zhou M. Topology optimization for shell structures with linear buckling responses. *Proceedings 6th World Congress of Computational Mechanics*, Beijing, China, 2004.

[18] Cevellera P, Zhou M, and Schramm U. Optimization driven design of shell structures under stiffness, strength, and stability requirements. *Proceedings 6th World Congress of Structural and Multidisciplinary Optimization*, Rio de Janeiro, Brazil, 2005.

[19] Taylor R, Weisshaar T, and Sarukhanov V. Structural Design Process Improvement Using Evolutionary Finite Element Models. *Journal of Aircraft*, Vol. 43, No. 1, pp. 172-181, 2005.

[20] Taylor R, and Weisshaar T. Merging Computational Structural Tools into Multidisciplinary Team-Based Design. *Proceedings 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Long Beach, CA, 2000