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New Approach to Improving the Aircraft Structural Design Process

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Reducing aircraft design cycle time while improving product quality requires improved information flow, process optimization, and use of advanced computational methods, including optimization, at critical times during the design process. Computer technology allows the use of highly precise mathematical analysis at all stages of product design. However, mathematical analysis must create added value that exceeds its cost. Selected Russian structural design research references are reviewed to show how novel ideas to improve aircraft structural design have developed during the past four decades. It is also shown how special purpose structural finite element models (FEM-1 and FEM-2), together with formal structural optimization during early design stages, improve integrated product team interaction, identify technical problems, and exploit benefits for conventional as well as radically new designs. This approach includes scientific weight estimation of critical components. The result is increased quality and reduced development time. Three examples illustrate this improved approach: a mounting bracket design, a fuselage bulkhead connected to a vertical tail, and a wing box design.

Introduction

PRODUCT design is both a scientific and a social/organizational process. Competitive success depends on blending the two processes together; as scientific and technological capabilities advance, the social/organizational process must consider changes to take advantage of the new capability. Major changes in commercial and military product development have occurred worldwide during the past decade, which places increased emphasis on product quality, reliability, and cost. Some groups within the Russian aircraft industry have responded to these needs. This response has included 1) the reorganization of the design process to insert finite element method information and formal mathematical optimization into the design effort very early, 2) the development of a useful structural optimization metric that parallels structural design experience, and the development of a semi-empirical weight estimation procedure based on formal structural optimization. This paper will summarize these developments and indicate how the current design process can be improved. The discussion will also review pertinent Russian research reports and papers not generally available in English translations.

An efficient organization with experienced, knowledgeable designers and analysts, equipped with effective analytical tools, is essential to high-quality product development. Between 1950 and 1990 military competition between the United States and the former Soviet Union, as well as the introduction of commercial jet aircraft into the worldwide air transportation system, produced numerous airplanes and fostered trained designers at all levels. The time between initial design inception and final testing was relatively short, while funding for new projects reached high levels.

Many of these highly qualified people have retired or are on the verge of retirement; they have not always been replaced with people with wide design experience. The number of new and projected military and transport aircraft has sharply decreased, but product requirements and complexity, together with the demands for reduced cost, reliability, and fuel efficiency continue to increase. The challenge today is not just to do things faster, better, and cheaper, within the allotted time, but to do it with fewer people with less experience than before and to provide experience and associated knowledge for younger engineers.

High-quality product development requires a wide variety of analytical methods ranging from simple first principles to sophisticated structural finite element methods and computational fluid dynamics codes. Analytical and computational methods supported by the computer are essential so that design features can be selected, scrutinized for adequacy, and then changed when defects or performance limitations are discovered. As a result, there has been an explosion of software development at all levels of mathematical complexity and model fidelity. On the other hand, some sophisticated software tools have failed to have a large impact on either product cost reduction or product quality. Part of this failure can be laid directly to the unwillingness or inability of the design and product development organization to use new products or to evolve and change as much as analytical technology has changed. Additional blame must be placed on software tool developers, who fail to understand the needs of the design process and the information required by the organizations involved in this process.

Effective product development requires restructuring the design and product development process to take advantage of the information produced by new computational tools. Gross[1] points out that companies that have successfully reengineered their business processes have adopted a "system oriented approach which focuses on the integration of all disciplines" and that their business processes are "re-engineered around a flow of information instead of a flow of tasks." This focus on information flow explains why some analytical tools are regarded as useful while others are not. Unless information is appropriate, meaningful, and comprehendible, it will languish within the organization that generated it, having no impact on product development. Design is not, nor will it ever be, a push-button enterprise.

Steward[2] discusses the design of complex systems such as aerospace products and reiterates the need for the timely generation and flow of information. Smith and Eppinger[3] stress the need for integration within complex processes that includes when to connect and when to disconnect integrated processes so that concurrent

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design makes sense and is executable. This involves planning and controlling information flow.

Although efficient computer applications are important to the design activity, computer tools and mathematical algorithms require humans to provide design definition and to provide the questions that analysis can answer. Formal optimization methods have limited use if the design objectives and design constraints are not clearly understood and completely stated. During early design activities, optimization methods are mostly directed toward defining external configuration details such as wing shape and size, but are not concerned with internal features such as structural layout or materials selection.

The choice of structural materials and the layout of load-bearing structure inside an aerospace vehicle have a far reaching impact on recurring costs and life cycle costs. For instance, during the conceptual design phase, empirical relationships, based on historical evidence, are used to compute structural and nonstructural weights with no precise idea about what the structural details look like, other than to assume that the structural design will follow company design tradition. Weight estimation errors of only a few percent can doom a design project by increasing its cost. Given the high sophistication of structural finite element analysis software, there is no reason why we need to rely solely on rudimentary empirical weight data for important decisions during conceptual design.

Traditional Structural Design Process: Six-Stage Process

To understand the need for change, let us look at the traditional airframe design process. The traditional airframe design process can be viewed as the six sequential, interconnected blocks shown in Fig. 1. Within block 1, the external shape is chosen with available customer primary requirement metrics, such as payload or seating capacity, and performance objectives, such as range and airspeed. Initial estimates of aircraft component weights using empirical data gathered from past experience are highly visible at this stage. If the design concepts considered have radical new forms, these estimates will be in error, and the effects and cost of these errors will appear during later design efforts.

The ultimate success of the design effort depends heavily on the training and experience of the design team assigned to the early design effort. Details needing attention that might escape the eye of a novice will be readily apparent to an experienced person. Cycle time and cost are extremely important, and so the analysis scope and complexity during early design is limited. In particular, only modest amounts of structural analysis are done, despite the strong correlation between aircraft acquisition and life cycle cost and the internal structural arrangement, materials selection, weight, and manufacturability. Even with today's extensive computer use, there is a long period of time during which errors in judgment can be introduced, discovered, and finally repaired. This approach to the design and development process wastes resources, consumes time, and ultimately reduces product quality.

Block 2 in Fig. 1 is concerned with internal structural layout selection. This is a complex process, particularly for components such as a fuselage that have many different types of loads applied. For the wing structure, layout or topology selection includes defining the number of spars and ribs and the location of critical system components such as landing gear and fuel tanks. The activities in block 2 are characterized by low-level structural analysis using simple idealizations for element sizing decisions. Seldom will the efforts in block 2 revisit decisions made in block 1. The level of effort required to conduct block 2 activities means that design efforts will require substantial effort to proceed beyond block 1 if the design is radically new and substantial risk is suspected.

Block 3 includes the extensive design activity required to generate detailed drawings of structural frames, ribs, spars, and attachments, as well as the documentation that must accompany these drawings. Block 4, the certification activity, requires extensive stress analysis with large, expensive finite element models developed from the drawings generated in block 3. Errors discovered in block 4 must be corrected by returning to block 3. Block 5 includes full-scale and component tests, including the fatigue and static loads. Errors here require revisiting both blocks 3 and 4. Block 6 represents the beginning of production and delivery to the customer. Unpleasant discoveries here will require revisiting several previous blocks, but never block 1. The cost of changes increases rapidly as the design effort migrates forward from one activity block to the next.

Internal Skeleton Structure Design and Weight Estimation

If a new airplane design closely resembles previous airplanes, a design team will have little difficulty generating design trade information. On the other hand, if the concept is radically new, such as the ground effect aircraft[4] shown in Fig. 2, the degree of uncertainty in estimating weight and defining weights trades will be high. The ability to generate scientific, so-called physics-based component weight estimates, as opposed to purely empirical estimates that are tied closely to a historical database, is a key need to new design innovation. For this exploration, we need the ability to design the internal structure (in Russia, this is called skeleton design) at the earliest possible time when the impact on major costs is the greatest. This involves finding an internal structural arrangement or topology that strikes a balance among low weight, cost, manufacturability, and performance requirements and constraints, such as flutter and growth margins.

Structural Concept Design

Definition of the skeleton structure requires the choice of load-carrying elements, for example, rods or panels, the way they are attached to each other, and the shape of the internal structure: the topology. The design of the load-carrying skeleton structure is an inverse problem that requires knowledge about the types, sizes, and locations of external applied loads because structural design is only as good and complete as the specificity of requirements and the external load environment definition. In practice, the initial geometrical layout of the structure is based on company design experience, history, intuition of the designers employed by the company, and subsystem integration requirements.

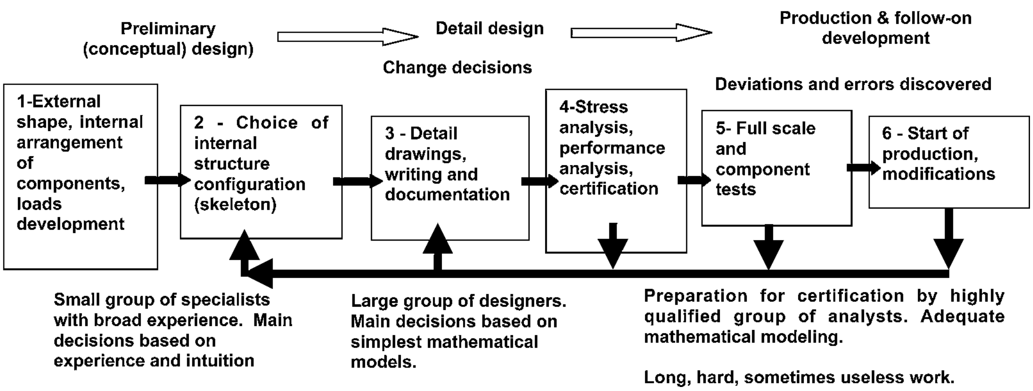

Fig. 1 Airframe design process block diagram.

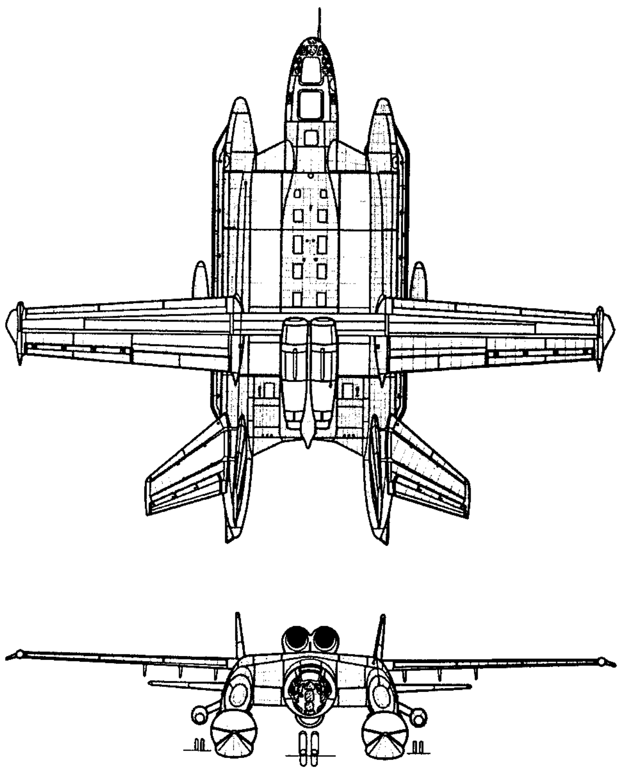

Fig. 2 Russian amphibian aircraft design.[4]

Aircraft design with a radically new external shape is complicated because of the requirement to identify critical applied loads; imprecise load definition makes structural and parametrical optimization less precise and less useful. This problem is exacerbated if critical load cases depend on the structural stiffness and deformation. For instance, loads applied to large transport planes during takeoff or landing involve interactions between the applied loads and the structural design. To calculate accurate takeoff and landing loads, it is necessary to add a landing gear model with nonlinear elements such as shockabsorbers and pneumatics. Structural flexibility determines these loads and reduces their magnitude in some cases by 10–15%. We can use early high-fidelity models to define load reduction in early design stages.[5]

Automated structural topology optimization is a research topic that has gained considerable respect and continues to have strong research interest. Commercial software packages exist to address the optimal arrangement of material in structures. Topology optimization research for Soviet aircraft began in 1952 with the work of A. A. Komarov[6,7] (the father of the present paper's first author). His approach, which was general and did not rely on any particular analytical method, was later summarized in a book printed for limited circulation within the former Soviet Union.[8] The theoretical fundamentals of structural shape optimization for thin-walled structures with isotropic or composite materials, based on the ideas of A. A. Komarov, were outlined later in the fomer Union of Soviet Socialist Republics by V. A. Komarov (the first author of the present paper).[9] This method was applied to the design of the Tu-144 wing.[10]

The result of this early work was a procedure that blends together human thought, experience and cognitive ability, and computer tools. Based on experience gained from some Soviet/Russian design experience, this is a four-step process, outlined in the next sections.[11]

Step 1: Defining the Design Space

A primary function of a structure is to provide resistance to external loads and to transfer these external loads from their application points to distant supports. In addition, the structure must fit within a limited space in which disconnected regions or volumes are excluded. To begin the structural design process, the allowable structural design space is completely filled with an elastic continuum. Because of the complexities of the analytical problem, we choose to develop a very general finite element structural analysis model, FEM-1. Little skill or design intuition are required to generate the FEM-1 model, but the analyst must understand design requirements and the proper use and limitations of finite element stress analysis packages. Previous experience may allow the designer and analyst to begin with an advanced structure such as a reinforced shell instead of a filled continuum.

Step 2: Formal Structural Optimization

When the FEM-1 model is used, the theoretically optimal structure (TOS) is found using formal optimization techniques. This TOS, as its name implies, is theoretical and is not intended to be the final structural design, but it provides load path, structural thicknesses, and a first structural weight estimate. Ordinarily, only stress and displacement constraints are used for this step, even though other constraints, buckling, for instance, will be added eventually.

Step 3: Load Path Information

The formal optimization exercise produces element thickness distributions. These thickness data are interesting, but not entirely descriptive when it comes to how the applied loads are absorbed by the structure and transmitted to supports. As a result, data from the optimal TOS/FEM-1 model are used to compute the magnitude and direction of the principal forces or main force flows (MFFs) within the structure. Principal forces are defined as the product of local principal stress times the element thickness. Principal force information displays internal force transmission patterns, the load paths, in the theoretically optimum structure. Because the optimal structure begins as an elastic continuum, skill and experience are necessary to define the real structure, which is a collection of interconnected elements. For this reason, the design team uses MFF or MFF patterns and the TOS material distribution to determine the best choices for structural elements, joints and attachments, and their locations in the actual structural design.

Step 4: FEM-2 Model

A new design model, based on the TOS, is generated at the beginning of this step. This design is a collection of interconnected elements and components. The finite element model of this design is called the FEM-2 model to distinguish it from the original FEM-1 structure. The FEM-2 is model developed by the design team as the result of experience, realistic manufacturing considerations, and special, perhaps unmodeled, structural constraints such as attachment and joining requirements. It is optimized using additional product requirements and constraints, for instance, buckling and flutter. When the complexity of the structure is considered, there may be a need to develop a FEM-3 or FEM-4 structure to address effects such as local buckling.

Example of Design Process

Our four-step process allows human cognitive ability to interact with computer analysis to allow a high-quality structure to evolve. The orderly evolution from the FEM-1 model to the FEM-2 design contributes to design quality. Because the evolution includes adding constraints and requirements, we do not expect the FEM-1 and FEM-2 designs to have exactly the same efficiency, but they should be close if information has been used correctly and consistently.

To illustrate our four-step design process for a simple two-dimensional design, consider the design of a bracket to transfer a single concentrated load to a wall support. This effort is shown in Fig. 3. In the traditional design process, an experienced designer would use past experience and design specifications to sketch the part; such a sketch immediately locks in topology, thicknesses, and other details. The analyst would then develop a FEM model to compute stresses. Changes in the initial design might be made, perhaps by resorting to formal optimization methods, although this is unlikely. The information transfer back and forth between the designer

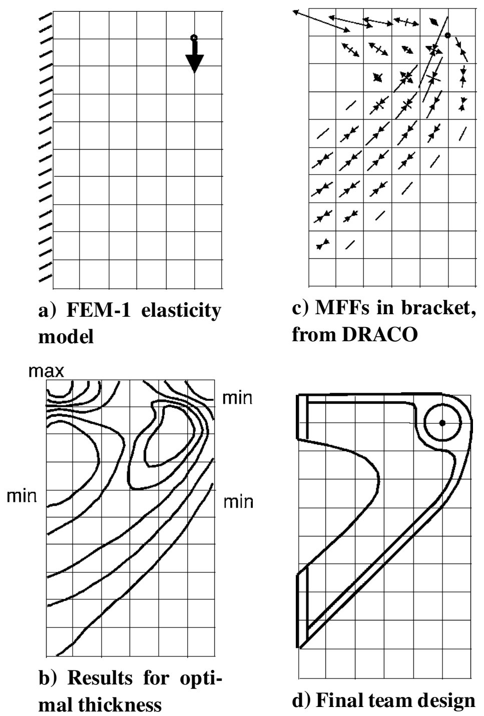

Fig. 3 Bracket design.

who draws and analyst who models and calculates might require several iterations, consuming valuable time.

For our alternative process, we first generate the planar FEM-1 model shown in Fig. 3a. This model consists of panels that resist shear and normal stresses. The geometrically allowable design space is filled with a continuous, constant-thickness, linear elastic material; it is isotropic, but could be orthotropic or even anisotropic. By definition, this continuum model and its FEM-1 counterpart contain all possible structural designs. Next, in step 2, formal optimization takes place with element thicknesses as design variables; material that carries little stress is automatically removed until the design space contains no wasted material. For formal optimization, we used a Russian optimization code, DRACO, although there are several commercially available computer codes in the United States for this optimization analysis.[12,13] The TOS for this example is shown in Fig. 3b. The resulting theoretical bracket structure is not usually a practical structure.

The MFFs in the TOS are shown in Fig. 3c. They define internal load paths in the optimal weight structure (note that some force flows have direction, but are not identified as tensile or compressive due to software limitations). This information helps the team to choose structural elements (truss elements, shear panel, etc.) to carry internal loads. The final finished product, shown in Fig. 3d, is the result of design team assessment of how to capture the theoretical optimal thickness distribution, deal with the MFF requirements and all other design requirements, including manufacturing and cost details. The FEM-2 model for this design is not shown, but is used to size elements in the final design.

Our second illustration is a more complex structure design problem, the design of a planar, internal rear bulkhead to carry loads from a vertical fin, idealized in Fig. 4a, into the fuselage skin. The vertical fin feeds a torsional moment, idealized as two concentrated forces from the T-tail, into the fuselage bulkhead, where it is then redistributed into the fuselage skin as shear flows distributed along the fuselage. Note that the loads are highly idealized, but could also come from more elaborate loads definition.

Traditionally there are two ways to design this bulkhead. The first is to use a mast scheme design where the fin structure penetrates all of the way from the top of the bulkhead to the bottom. A second candidate design is a frame that penetrates only half way through. Each design has merits and can be optimized, but which is best and more natural?

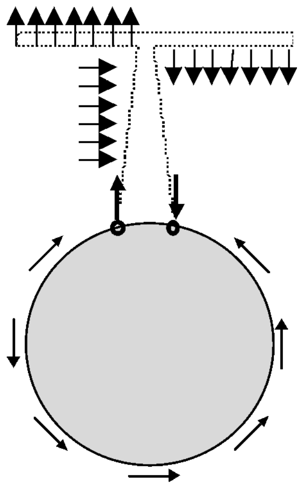

Fig. 4a Fin design example.

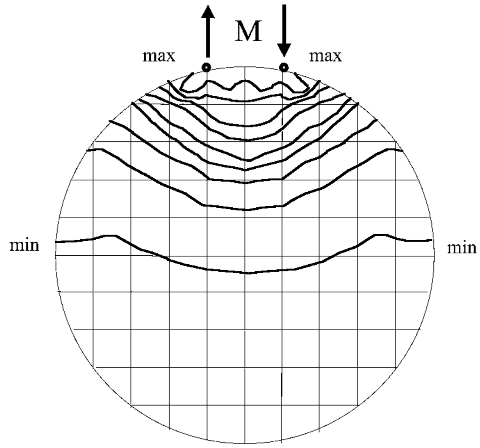

Fig. 4b FEM-1 mesh and TOS results.

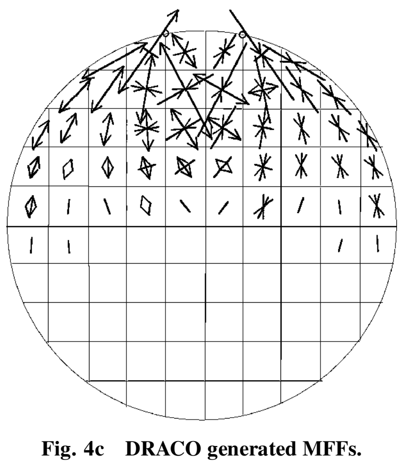

Fig. 4c DRACO generated MFFs.

The design process begins with the FEM-1 model, shown in Fig. 4b. The FEM-1 model is a planar ring filled with a grid of constant thickness, elastic panels that resist shear and normal stresses. This grid is attached to a short shell, lying out of the plane, to simulate the monocoque fuselage. Figure 4b also shows the results of the DRACO FEM-1 panel thickness optimization; the dark lines represent lines of constant bulkhead thickness. The FEM-1 optimization model shows that the fin loads are resisted in the bulkhead structure by internal forces located almost entirely in the upper part of the allowable design space.

Figure 4c shows the MFFs in the optimal structure generated by DRACO. (Arrowheads are missing from some of the lines because of a DRACO display problem near some boundaries.) These

MFFs have substantial tensile and compressive components, which indicates that internal shear loads predominate in the interior of the bulkhead and a shear panel is required for the bulkhead design.

The final bulkhead design is shown in Fig. 4d; it is an effective least-weight half-mast design scheme. Unlike the initial design, the final design is a product of team effort that considers cost and special requirements not captured by formal optimization. There is a substantial visual difference between the final design and the theoretically optimal structure. On the other hand, the internal force flows in the theoretical and the practical designs are similar.

This same procedure can be applied to complex wing structures; a FEM-1 wing box model with the optimized structure MFFs is shown in Fig. 5. This FEM-1 model represents the wing box structure whose forward spar is located at the 15% chord position and rear spar is located at the 80% chord position. The wing also carries a tip store. The designer has recognized that the structure will be a reinforced shell and so the FEM-1 model is composed of sandwich panel elements whose skin thicknesses are optimized to resist only a pitching maneuver, although the formal optimization problem could be extended to include several load sets. In that case, there would be MFF diagrams for each load set. These results indicate the need for at least three spars because the loads have a substantial path leading to the box center. Several FEM-2 designs may emerge from this starting point, depending on the makeup of the design team and the questions that need to be resolved.

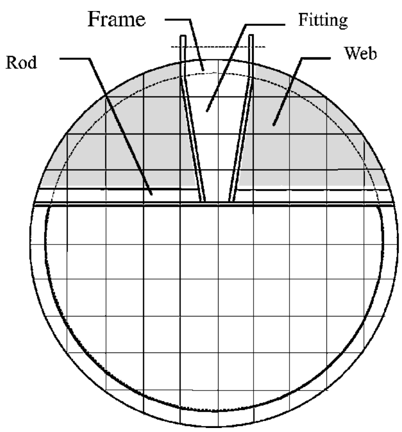

Fig. 4d Final design.

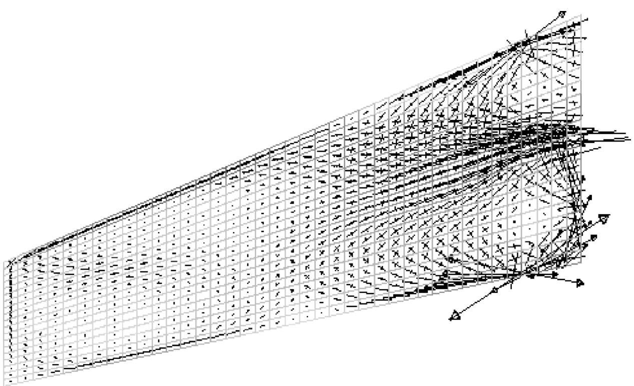

Fig. 5 Wing planform FEM-I results showing MFFs on upper wing skin.

These examples suggest the new structural design paradigm shown as the blocks in Fig. 6. Block 1 contains the usual conceptual design activity in which different geometrical forms are created to meet perceived mission requirements. Block 2 activity begins immediately after results from block 1 are available. Loads are generated, together with FEM-1 models, to create the MFFs and the TOS. The addition of block 2 to the process requires extra time to prepare a relatively simple finite element model and mesh (FEM-1) and to conduct optimization exercises. FEM-1 model optimization enables the design team to find quickly the theoretically optimal structural material arrangement and to use MFF information to inform the design team of any special needs. The results of block 2 are also used to estimate and compare component weights for different options developed in block 1.

Block 3 activity involves design of the actual structure. This activity relies on team members to develop the more realistic, higher-fidelity FEM-2 model; this model uses formal optimization algorithms and employs additional constraints. The remaining blocks proceed as usual, but with the promise that many issues have been resolved and will not reoccur. This new process allows the design team to avoid mistakes, shorten the design cycle time required to create the new structure, and reduce risks while improving quality.

Semi-Empirical Construction Factors for Weight Estimation

The theoretically optimal structure generated with the FEM-1 and FEM-2 structural models provides estimates of the theoretical structural weight. The final manufactured weight of a component is always greater than the theoretical weight for two reasons. First, the actual structure will differ from the theoretically optimal because of manufacturing requirements that usually preclude features like continuously varying thicknesses. Second, the theoretical structures do not include the weight of details such as stiffeners, items such as fasteners, or non-structural parts. In addition, the models may not include some design requirements or constraints.

The ratio between the real weight and that theoretically necessary (from the FEM-1 or FEM-2 models) is expressed as

$$\Phi = W_{\text{real}}/\rho V_{\text{theor}} \tag{1}$$

The denominator is the product of the volume of the TOS and the density of the structural material.

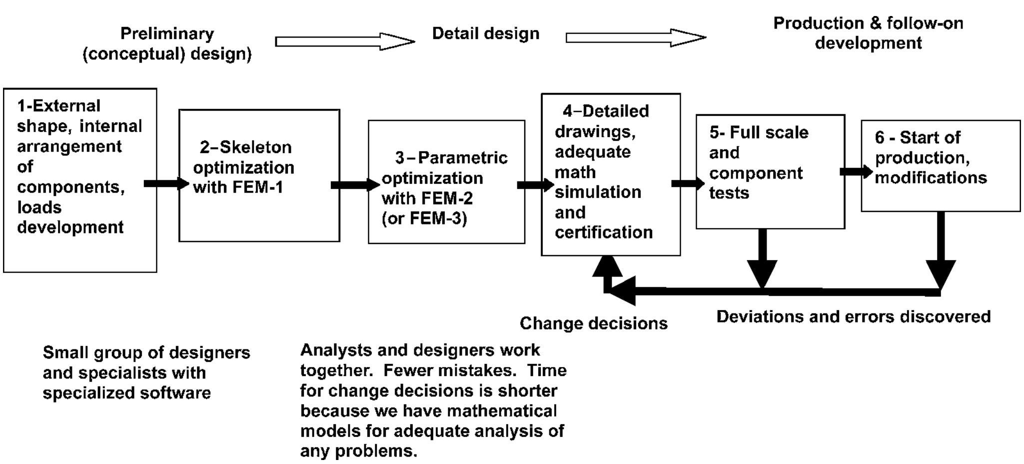

Fig. 6 New airframe structure design paradigm.

The ratio Φ is called the construction factor; it is empirical and has a long history dating back to Soviet railroad construction.[14] The construction factor Φ depends on the type of airplane (transport or military), the component (fuselage or wing), the quality of the design effort (including the experience of the team members), and the manufacturing methods. If the structure is simple, for instance, a bulkhead, the construction factor will be closer to unity than if it is a more complex structure, such as a wing or a fuselage.

The calculation of Φ is more accurate for FEM-2 models because they represent a closer relationship between reality and theory. Extensive research and experience from Soviet/Russian design bureaus shows that Φ can be calculated reliably using the historical, after-the-fact analysis of an actual airplane if we have four items available[15]: 1) drawings to define the structure (preferably the FEM-2 model), 2) actual airframe component part weights (both structural and nonstructural), 3) critical external design loads, and 4) allowable stresses used to design the airplane structure. If the parameter Φ is computed after the fact, then the most labor-consuming operation is the creation of the FEM-2 finite element model to determine the theoretical optimal structural weight with appropriate constraints. In some cases, such as the bulkhead example, this is not a problem. However, for a complicated device such as a wing, it is more laborious, although it is possible to use relatively simple, coarse models for this purpose if the FEM-2 model has not been used in the design process.

Figure 7 shows coarse finite element models for two different Russian aircraft wings and one horizontal stabilizer and the values of Φ associated with these designs. Unpublished data for 10 wings and stabilizers of Soviet subsonic transport airplanes found values between $\Phi = 2.40$ and 2.43. This is a narrow range and perhaps the result of good design practice. (Note that the unpublished reference that produced the finite element models shown in Fig. 7 was unclear as to whether these were the actual coarse models or simply notional representations. However, the construction factor data was evidently carefully prepared.) In one case, not shown, a Soviet passenger airplane wing designed about 40 years ago had a value $\Phi = 2.14$; this design was done by a team that emphasized weight minimization throughout the design process. From this we can infer that construction factors depend on the team leadership, the technical tools available to them, and perhaps the degree of maturity of the design requirements.

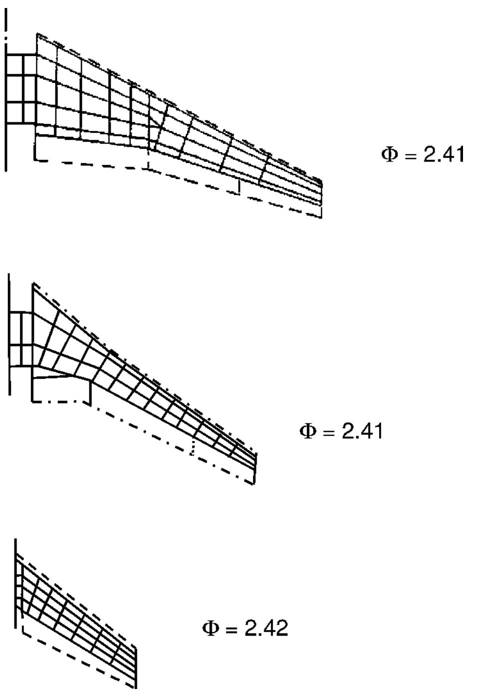

Fig. 7 Aircraft wing structural designs and construction factors Φ (drawings are approximately the same scale).

These examples indicate that Φ has relatively large values for complex structures. A partial explanation for this large ratio between real and theoretical is that there are forces at work, engineering or social, including manufacturing, that are not captured by finite element modeling and optimization. The other explanation is that other, nonstructural, items add up quickly and that the structure itself, however good, is a small part of the system optimization process.

Fuselage weight estimation and the optimization of the fuselage structure is a much more difficult exercise than wing design[16] because of the wide variety of applied loads and local external features such as windows and access areas. A review of available Russian designs shows that three Soviet/Russian airplanes had values of Φ between 2.63 and 2.85. We believe that the parameter Φ is a useful metric for assessing final design quality. A second design quality metric is the load-carrying factor (LCF), discussed in the next section.

Load-Carrying Factor (LCF), *G*, Metric for Design Optimization Quality

Good design practice emphasizes creation of short load paths to transmit external loads to internal supports. Formal optimization requires a performance index to be minimized or maximized We would like to use a formal metric that compares well with what the designer instinctively feels is good design practice, such as the desire to have short, effective load paths. A Russian metric related to both structural efficiency and least weight is the LCF G. The LCF metric is the product of the value of internal stresses (or forces) in an element multiplied by the length of their action; it is related to component weight by the following relationship[8]:

$$W_{\text{real}} = \Phi \cdot \rho \cdot V_{\text{theor}} = \Phi \cdot \rho \cdot (G/\sigma_{\text{allow}}) \tag{2}$$

when it is assumed that there is a single allowable stress σ_{allow}. For a multielement truss structure, G is defined as

$$G = \sum_{i=1}^{n} |N_i| l_i \tag{3}$$

where n is the number of structural elements, N the internal element force, and l_i the element length. Equation (3) has the appearance of an expression for work (force times distance). As a result, it reflects the desirability of having short load paths, but also takes account of the magnitude of the internal loads required to follow that path. A long path with small internal loads is as desirable as a short path with high loads. For thin-wall structures, the LCF is defined as

$$G = \sum_{i=1}^{n} R_i a_i \tag{4}$$

where

a_i = structural element cross-sectional area
R = equivalent force flow, $t \cdot \sqrt{(\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2)} = \sigma_{\text{eqv}} \cdot t$
σ_i = principal stresses
t_i = thickness of structural element

In the most general case, G is an integral written as

$$G = \int_V \sigma_{\text{eqv}} \, \mathrm{d}V \tag{5}$$

where V is the volume of load-carrying material of the structure.

G depends on internal structure topology, that is, the type of elements, their number, their connections to each other, their arrangement in space, and their cross-sectional areas or thickness. As design and optimization progresses, G should decrease. Element cross-sectional areas (and their internal forces) will change during optimization, but experience shows that G for the whole structure converges quickly, changing only by a few percent after the first few design iterations, even though some element volumes increase or decrease. As a result, we can evaluate the quality of a structural arrangement (and the weight) with high fidelity from only a low level of computational and modeling effort.

Even for complex structures such as reinforced shells, G can be calculated with high accuracy using a coarse finite element mesh. This makes an objective comparison of two different structural geometries possible. Experience with both swept and delta wings shows that acceptable accuracy for G can be obtained using finite element meshes with numbers of elements of the order of $n = 100$, whereas wing strength analysis demands much finer meshes, two orders of magnitude larger, of the order of $n = 10{,}000$.

In summary, the uses of G and the construction factor Φ include the following.

1) Use G to compare the effectiveness of different structural load-carrying arrangements. In early design stages we can use G as a metric to compare alternative structural load-carrying arrangements. The calculation of G for each design option using coarse finite element models allows well-reasoned choices without extremely detailed models.

2) Use Φ for quality control during detail design. Before developing detailed structural drawings, we can use the FEM-2 model and Φ for the structural design weight to see how the team has progressed toward its weight targets. After the design has been built, the calculation of the actual value of Φ defines the quality of the company team effort. This metric can make design evaluation more scientific and can be used as a measure of quality. For instance, if one effort yields a construction factor of 4 and another gives us 3, then it is fair to ask about the differences between the designs.

3) Use Φ to predict airframe weight early. Weight estimation early in the design effort must always contain empiricism.[17] However, the construction factor Φ concept allows us to explore new designs with greater confidence because one portion of the estimation equation is based on well-defined structural geometry specific to our design; we can predict with confidence how changes in the geometry will change weight.

Summary

Computer analysis, including efficient database generation and formal multidisciplinary optimization, provides enormous capabilities to a design team. On the other hand, the availability of powerful software tools makes it imperative that we ask how the organization of engineering design efforts will use these tools and will change as more new tools become available. In the work discussed, the creation of the FEM-1 and FEM-2 models is a scientific way for beginning structural optimization and integrating it into the design effort, while still retaining and increasing human creativity and innovation.

Our approach allows the team to prepare an accurate theoretical estimate of the best design topology and minimum weight of a structure and will provide better weight estimates early in conceptual design. The effectiveness of this approach has been tested in Russia; the references cited in this paper are overwhelmingly written in Russian, most before 1990.

Creation of the FEM-2 model before the development of final drawings (Fig. 6, block 3) is much easier than creating a similar model based on drawings in the traditional design sequence order (Fig. 1, block 4). As a result, FEM-2 should drive the drawings, not the other way around. FEM-2 for parametric optimization and detailed design is also required for quick analysis of the causes of failure and deviations in the behavior of the structure found during full-scale testing of the structure (as a whole or as components). The detailed FEM-2 is kept during the entire product life cycle. It requires extra effort, but the payback period is short because it reduces the time spent resolving unanticipated problems.

Finally, note that one person's FEM-2 model is another's FEM-1 model. The level and complexity of the initial discrete models will depend on the experience of the organization and the design freedom that they have to create new forms. In addition, load case descriptions during the early design phase require highly qualified specialists. It is imperative that the people who provide this information become active parts of the design team from the beginning and continually update the loads. The promise for the future is the rapid generation of high-quality designs and an accurate, fair evaluation of innovative concepts for aeronautical and aerospace designs.

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