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Structural Design Process Improvement Using Evolutionary Finite Element Models

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This paper describes a process to enable a multidisciplinary design team to address a wider range of structural design requirements much earlier in the design process than is common today. This process uses "structured design" methods that incorporate information generated by finite element analytical methods into team decision making. The proposed process defines and then addresses major structural requirements such as deflection and stiffness constraints early in the preliminary design process so that their effect on wing weight and manufacturing cost is known very early in the process. To test the proposed design process in an industrial environment, an on-site experiment was conducted involving design of a wing internal structural layout, including how many internal spars were to be used and where they were to be placed, for a proposed business jet. The experiment, although limited, showed that the new process could provide decisive advantage in terms of organizational needs, time required to produce an effective design, risk reduction, and product quality improvement. The results of these efforts further indicate that the proposed systematic, evolutionary structural design process rapidly focuses discussion, analysis, and decision-making efforts to produce a low-risk, viable design by identifying and resolving structural and manufacturing issues early in the design process. It also indicates that the insertion of finite element analysis very early in the conceptual design process provides major interdisciplinary benefits, allowing teams to identify weight and cost issues early on.

Introduction—Competitive Design for the Future

AIRCRAFT design efforts evolve from simple "sales" sketches, with a few people involved, to more detailed phases that include consideration of internal geometry and mission performance, requiring large numbers of specialists and a large financial risk. During this design progression, the number of design requirements, including those from aerodynamics, structures, external and internal loads and finally, manufacturing, increases rapidly. In the very early design phase, designers make decisions and change design features relatively easily, often with the stroke of a key on a keyboard. However, the design requirements information and the design details provided to address these requirements lack the fidelity to fully evaluate the impact of early decisions on final product viability and quality. When design fidelity appears later in the process and errors or omissions are noted, the cost of design changes is large, and their impact can be so severe that the design is abandoned.

Some design decisions are made ad hoc, on the basis of past experience, or are based on empirical models or analytical models that later prove to be inadequate or misleading. In addition, the aversion to taking risks that can jeopardize a company, should the design fail, often delays the incorporation of new technologies into new products. Whereas risk is reduced by using only proven technology, if new technologies were used in new designs, the resulting product would give the company a decided competitive advantage.

Because design is both an organizational and a technical activity,[1] successful design processes must integrate people, analytical tools, experimentation, and information. The design process, through customer-oriented requirements and design traceability, must also have a well-defined structure to define and then provide exceptional quality, measured against customer needs and requirements. Experienced designers are essential, but experience is a double-edged sword. Experience keeps a company from making the mistakes of the past, but it can also prevent a product team from taking advantage of opportunities for the future if the team is risk adverse.[2]

Although aircraft design is an iterative process, decision making is sequential, even though many related efforts are conducted in parallel with many important decisions being made out of sight of other team members. Aerodynamic configuration and estimated performance must always come first, but it is the structures design effort that determines important metrics such as final weight and manufacturing cost. The timing of when structural details are generated and when they are revealed to the design team is crucial to a successful design effort.

Design Problem

This research focused on the solution of an organizational and technical problem—the design of an advanced business jet wing with a team that involved members from two different experience backgrounds. Part of the team came from a culture that favored multispar design, preferring a many-spar concept, whereas others came from a different culture that favored two-spar wings. Technical expertise for the design project included experienced personnel from aircraft loads, structural integrity, producibility engineering, and airframe design.

Because of the different experience bases, there were conflicting opinions about the number of spars to be used in the wing. Resolving this disagreement requires defining and examining the relationships between the number of spars, manufacturing cost, wing weight, and

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aircraft performance. This definition and the trades required are usually not provided at the early phases of project development, but even if they are not, then the decisions are usually made using simple voting with incomplete information, a process that needs improvement.

The use of so-called "structured design methods," to be described later, brings an effective organizational component to the design process. Added to this process is accurate structural information, including weight estimates and costs. Structural analysis information is provided by finite element method (FEM) analysis. The result is a set of structured design phases in which FEM information is used and then modified as each design phase is entered or exited. This phased process is described in an ensuing section.

Because this investigation focused on design of primary wing structure, it considered additional structure only when it affected wing structure through interfaces or constraints. As a result, although flap and aileron structure was not considered, loads from flap and aileron attachments were applied through flap tracks, hinges, and actuators as appropriate.

Defining an accurate, representative set of load cases is critical to designing a structure, but, in the beginning, too many loads with too much fidelity restrict the ability to explore the design space during conceptual design. Conversely, insufficient fidelity, in terms of the number of loads considered or their accurate distribution, leads to missed or misplaced structural connections and a poor design that must be corrected later. Requirements for the wing structural design fall into the following categories: 1) structural performance (stiffness/deflection, strength, durability, structural stability, geometric interface) 2) environmental; 3) loads (ground wind gust durability and protection, lightning-strike protection, ice protection, fuel slosh and vibration); 4) size (dimensions, weight, fuel volume); 5) costs (recurring costs, direct operating costs, producibility and process characteristics); 6) support (service life, structural inspection, towing, jacking, and hoisting, reliability, maintainability); 7) safety (system safety, fire safety, crash safety, bird strike, emergency egress); and 8) certification.

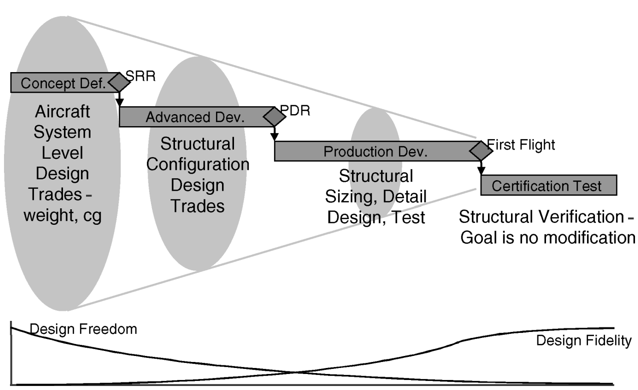

Fig. 1 Design process structural needs.

Loads for the model conceptual wing structural design came from existing aerodynamic panel method pressure distributions for a similar wing with five different flight conditions. For simplicity and design freedom, our experiment used the conservative approach of considering only aerodynamic loading while neglecting inertial effects. A previous Raytheon Aircraft study had identified the load cases causing extremes in shear, torque, or bending on an existing wing similar to the model wing in this experiment. These results were used to define five load cases: 1) static landing with flaps—maximum positive torque and shear; 2) head-on gust, landing with flaps—maximum negative torque; 3) dynamic gust at cruise—maximum negative bending moment; 4) dynamic gust at cruise—maximum positive bending moment; and 5) static maneuver—maximum positive torque and shear.

Structural Design Approach—Information and Requirements

Because structural design is not normally considered to the extent we propose in our process, it is useful to consider how the process can be improved. The systems engineering process[3] provides formal organizational procedures to evolve design detail and link the flow of information to promote successful design activities. As shown in Fig. 1, the ability of the system design to evolve from simple concepts to working details places requirements on the structural design process, from early design trades to detail design and verification later in the process.

Structural design places expectations and demands on design and analysis tools, the mathematical models that form their core, and the people who use the tools to generate information. As shown in Fig. 2, structural models must satisfy systems engineering process needs by having the ability to evolve from simple conceptual models—to enable rapid exploration of the design space—to detailed designs that refine, test, and validate design concepts before they are built. Many of these models do not have features that promote an easy or swift exchange of data from one to the other.

Information quantity and quality increase and the sophistication of analytical techniques will evolve as the design progresses through the design funnel in Fig. 2. Analytical tool evolution begins with elements such as engineering beam models and stress handbook formulas that are simple and appropriate to the level of external

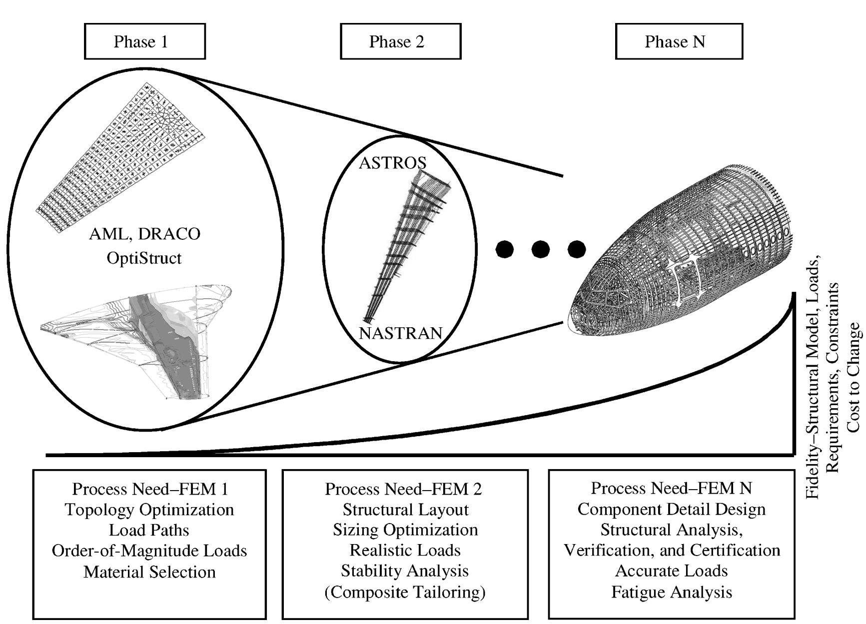

Fig. 2 Structural design funnel.

loads definition and geometry. For instance, at the beginning of a design effort, it makes no sense to have an exquisitely detailed stress model when the loads are not defined to a similar level of detail.

At the beginning of the structural design process (phase 1 in Fig. 2), structural designers need basic information to guide configuration and topology decisions such as how many ribs and spars are required, where they are located and how they are oriented. Phase 1 requires experience and creativity and a clear understanding of process needs and analytical tool requirements for wing structural design.[4]

The latter parts of the design process (phase 2 through phase N in Fig. 2) involve detailed structural member sizing, optimization, and analysis. Decisions made during all of these phases have a crucial effect on aircraft weight, performance, and manufacturing cost.

Weisshaar and Komarov[5] suggest reorganizing the traditional aircraft structural design process to include FEM earlier in the conceptual design process. A central feature of their process is the generation of load path information using formal optimization techniques and finite element models with general features, such as closely spaced ribs and spars, that span the design space with many more design degrees of freedom. For wing design, these design degrees of freedom, including the number of spars and their position within the structure, are elements of the topology design process. When formal analytical optimization methods are employed, with relatively accurate load sets, finite element model analysis will show how material would like to distribute itself in an ideal world in which one could design the structure with only well-stated mathematical constraints. This provides information on "natural" loads paths within the structure and where the load paths naturally want to develop, given a basic set of geometric constraints including landing gear cutouts and fuel placement, but without consideration of manufacturing or other real-world requirements. Komarov and Weisshaar refer to this first, very general structural model as the FEM I model.

When provided with FEM I theoretical information, experienced structural designers then use their experience and the load path information as the basis for the design of the actual structural configuration. If the design concept begins as a well-developed, well-researched concept, this initial modeling step is not required and probably wastes time. However, when the design activity involves new materials or new geometry, this initial step provides the team with a great deal of new knowledge that can lead to new design concepts. The FEM I model contains very accurate external geometry information so that it can be rapidly reformulated to produce a new detailed finite element model, called FEM II. This model has additional constraints and loads added and is used to size internal members while adding. The transition from FEM I to FEM II is an evolutionary step that preserves information while providing a seamless approach to adding fidelity.

Improving the Design Process Through Formalization

The value of information increases when it is used in a structured, formal process. The system approach to the design process is discussed in detail in references such as Ulrich and Eppinger,[6] Eppinger,[7] Pugh,[8] Dym and Little,[9] Cross,[10] Alexander,[11] and Simon.[12] Design efforts require both problem definition and solution synthesis, each of which can be improved through a structured, systematic approach .

Problem definition includes problem decomposition in terms of functional, requirement, and/or physical hierarchy; identification of requirements; identification of information needs, dependencies, and conflicts; and specification of the level of definition of the end product (i.e., design fidelity at end-of-phase gate). Systematic methods to develop the design problem objectives and scope include quality function deployment[13] for requirements definition, and design structure matrices for information dependency and process mapping.

Systematic definition, exploration, and evaluation of design problems and solutions promotes completeness in representing the customer's needs and fully exploring the design space. This effort used structured design methods to develop the organizational aspects of their design activities. By providing an organizational framework and process for moving forward, structured methods improve team effectiveness by formalizing and managing information flow among the team members. Systematic approaches are self-documenting and preserve learning and knowledge gained from each design stage or phase. Systematic approaches clarify the "voice of the customer" so that team members can understand how their effort and function adds value to their product. This provides focus and places the quality issue within the scope of early stages of the design process; this is much more effective than "fixing" deficiencies in the design product after the fact as more customer requirements are unearthed.[14]

Solution synthesis requires generating a wide range of concept solutions to the design problem and then evaluating them against the customer requirements. Systematic methods for solution synthesis include basic concept screening and scoring matrices, Pugh[8] concept selection, and concept morphology tables. These scoring matrices require accurate information to enable team interaction and discussions that have a meaningful outcome. Every requirement cannot, and should not, be addressed in a scoring matrix because not all requirements differentiate design concepts. Requirements against which concepts perform equally well do not merit evaluation at this point in the process. A notional example of a scoring matrix result, but with insufficient information, is shown in Table 1. Later, we will use this same type of scoring matrix approach to illustrate how adding information adds value.

The scoring matrix is a means of displaying team preferences. The purpose of the scoring matrix in the list of requirements for wing structural design is to attempt to decide which of four different wing layout concepts best satisfies the customer. However, this particular matrix is notional in that it depicts what might happen without accurate structural analysis information.

The systematic process works as follows. The team first defines elements of customer quality and lists them as rows in the matrix. The relative importance of these elements is determined by team discussion, balloting, and consensus. Wing structural concepts are

Table 1 Scoring matrix with low-quality information input

Design concerns	Weight factor	2 Spar		3 Spar		4 Spar		7 Spar	
		Raw	Wtd	Raw	Wtd	Raw	Wtd	Raw	Wtd
Weight	0.30	0	——	0	——	0	——	0	——
Stiffness	——	0	——	0	——	0	——	0	——
Fuel volume	——	4	——	3	——	2	——	1	——
Cost	0.30	3	0.90	2	0.60	2	0.60	3	0.90
Fabrication	——	4	——	3	——	2	——	1	——
Assembly	——	1	——	2	——	3	——	4	——
Accessibility	0.05	4	0.20	3	0.15	2.5	0.13	1	0.05
Inspection	——	4	——	4	——	2	——	1	——
Maintenance	——	4	——	2	——	3	——	1	——
Fuel considerations	0.05	2	0.10	4	0.20	3	0.15	1	0.05
Certification Issues	——	——	——	——	——	——	——	——	——
Fail safe	0.25	1	0.25	4	1.00	4	1.00	4	1.00
Verification	0.05	4	0.20	3	0.15	2	0.10	1	0.05
Weighted sum	1.00	——	1.65	——	2.10	——	1.98	——	2.05

generated by the structures team members and presented to the rest of the team. Each of these concepts is discussed and compared within each of the customer requirements categories. The team uses a scale of 1 to 4 to evaluate a concept; 4 is best. These raw scores are then multiplied by weighting factors, as determined by the strategic objectives for the aircraft product in the marketplace. In this case, the team placed greatest importance on weight, cost, and certification.

For each concept, the team generates numbers in each column that reflect team evaluations; the results are then weighted and added. At the end of the process, the team will have thoroughly discussed the concepts. If the systematic team scoring process works, from this discussion and by comparing weighted, composite totals for each design, the team can make an informed choice.

Low-quality inputs into this matrix will produce numerical results with little differentiation among the concepts. This is the case in the notional example presented in the structural design requirements list when structural information is not provided to the team. The sum totals in the bottom row are so close that, unfortunately, the process will produce a great deal of discussion, many meetings, but no basis for a rational, consensus design decision. In this notional example, weight and cost cannot be differentiated because no accurate models are available to provide information that differentiates one spar design from another. The result is that strong opinions of team members prevail, but no scientific way of resolving the conflict is evident. Our proposed method will resolve this problem by providing the required information about the structure, including weight and cost.

This outcome is predictable becasue there is an unbalance among the inputs into a decision-making process. Waszak et al.[15] identified this same problem when they used a systems approach[16] to model multidisciplinary team dynamics; they identified six key team effectiveness determinants. Two of these determinants are 1) effectiveness of team processes and 2) balanced level of technology. The insertion of new conceptual structural design tools into our wing design process can improve the "balanced level of structural technology" determinant and provide better results when used with the structured process described.

Lack of accurate, meaningful data tailored to the decision purpose will also result in lack of involvement or commitment by those team members who need the data. This so-called technical deficiency problem appears when the level of technology for a multidisciplinary task is below the level required for an expert to commit to a decision.[14] Providing a balanced level of technology information places all disciplines involved in multidisciplinary design at an equal, acceptable level of technical deficiency. Modern structural design tools raise the structural technology level closer to that of other disciplines that traditionally dominate conceptual design decisions.

Design Experiment—Testing a Design Process

A wing design process was developed using well-established ideas from previously cited literature. This process formalizes the wing structural design process and separates it into several different phases, each with its own objectives and information needs. Within each of the design phases there is a FEM whose features are dependent on team decisions within that design phase and that can evolve as design efforts progress. Results of these analyses feed into the team effort and furnish information for the design scoring matrix.

A key question is "does this approach add value in the real world?" To answer this question, a team was assembled at Raytheon Aircraft to consider the wing design problem discussed earlier. The following sections discuss the approach and the results of the process experiment.

Cost-effective structural models must evolve so that low-order features, desirable for conceptual design trade studies, can be replaced with more fidelity as the design effort progresses—without substantial rework of the substantial model input required to build the first model. Totally discarding models means that there has to be an added investment of time to carry over and expand details from one stage to another. For example, finite element methods require detailed geometric models that, in turn, require large time investment. As a result, modern structural design tools usually enter the design process only when conceptual, system-level design is finished or nearly concluded; their impact on aircraft configuration design is minimal. By the time finite element results are used, the design team has already committed to the main elements of a structural configuration. This effort used a series of models of increasing complexity that helped the multidisciplinary team.

Figure 3 depicts the cycle of design and structural analysis activities. In our process, structural detail evolves through a series of finite element analysis and optimization activities (FEM 1-FEM N). These models, their constraints, and details are modified and improved, but not discarded, as team-based design activities progress from design 1 to design N.

The process depicted in Fig. 3 allows a natural evolution of structural detail. The first level of detail uses structural members driven by stress and includes placement of spars and spar webs and determination of required skin thicknesses. The next level of detail adds buckling and deflection constraints, requiring inclusion of rib and stiffener design into the process. The following sections describe goals and actual outcomes of each phase of the design process with team results from each phase.

Requirements Definition

The wing structural design activity has weight and cost objectives, but must meet aircraft mission and certification requirements and

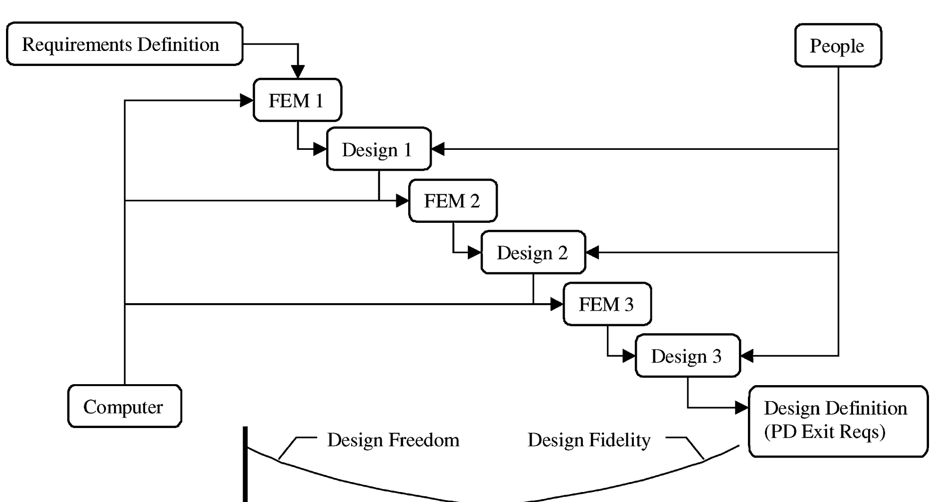

Fig. 3 Alternating evolutionary finite element models and design activities for design process experiment.

constraints. To begin the process, a wing structural requirements document was developed to provide metrics and to communicate design needs to project participants. This document established metrics such as maximum tip deflection, including target values. The requirements established by this document flow to lower-level design activities as part of the systems engineering process.

Phase 1

The goal of phase 1 activities is to provide strong, scientific theory-based structural feedback—tempered by designer experience—during aircraft system-level design activities. Traditionally this activity has only historical weight and center-of-gravity structural input. To influence outer mold line design, phase 1 models and methods must provide meaningful structural design options and feedback as early as possible, but with as little internal geometric definition as possible.

The first finite element model, FEM-1, is used to generate and convey information about preferred load paths in a very general structural domain, in this case a shell with a general support structure enclosed, with minimal initial structural definition, but accurate outer moldline fidelity. Our experiment used a NASTRAN-based model with a modified method of feasible directions optimizer. The load paths are computed after structural optimization that shows where material should be located in an ideal structure. The load path computation provides information about optimal, least-weight locations for stress-driven primary structural members; these include spar web positions and skin thickness buildup from outer wing panels to wing-root panels. The FEM-1 model is the starting point for structural concepts and forms the foundation for structural topology design evolution.

The FEM-1 model has a shell skin with in-plane normal and shear stiffness and a core with out-of-plane normal and shear stiffness, as shown in Fig. 3. The FEM-1 model provides a theoretical weight estimate of nonstructural mass that can be related to the actual wing weight. The theoretical structural weight estimate is incomplete, but serves as a valuable metric to track the effect of each added constraint set at higher levels of fidelity.

The structures designer provides the FEM-1 model and its information to the full team for design 1 activities to generate spar web and rib structural concepts. Structured design methods for concept generation, evaluation, and selection help to communicate and leverage this information for effective design decisions. The analytical structural information that results from the FEM 1 model forms the basis for level 2 concept generation.

FEM-1 Results

Structural modeling for FEM 1 allocates bending and in-plane shear carrying capability to the wing skins and out-of-plane normal and shear carrying capability to a core filler material as shown in Fig. 4. The initial FEM 1 model used shell elements for the skins and orthotropic brick elements for the core. However, in this model shear stiffness in the core changed direction with element skew and orientation.

To circumvent this problem, a modification of this FEM 1 model uses a lattice of chordwise and spanwise shell elements between each brick element in the core as shown in Fig. 5. These shell elements have controllable directional shear stiffness properties while the brick elements have out-of-plane normal stiffness. Figure 6 shows the actual FEM 1 model used for this experiment.

The force flow information is displayed as plots of maximum and minimum shell forces in the skins. Figure 7 shows shell force plots for the positive dynamic gust load case applied to the FEM-1 model. Figure 8 shows the skin thickness distribution optimized over all four load cases.

The wing structural box weight computed from FEM-1 was larger than expected. One reason for this discrepancy is insufficient fidelity in the optimization model, causing high skin thickness over large regions because of local stress concentrations, both computational and real. In addition, a low allowable stress constraint used for the FEM-1 model. The low stress constraint was used as a surrogate for durability and damage tolerance requirements.

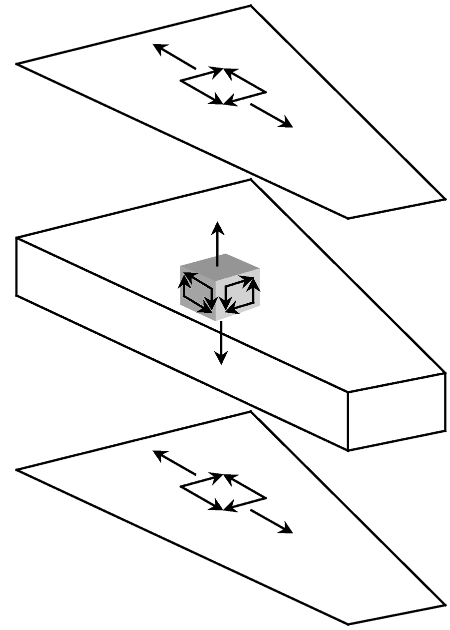

Fig. 4 Initial FEM 1 model showing upper and lower skin with in-plane normal and shear stiffness and core with out-of-plane normal and shear stiffness.

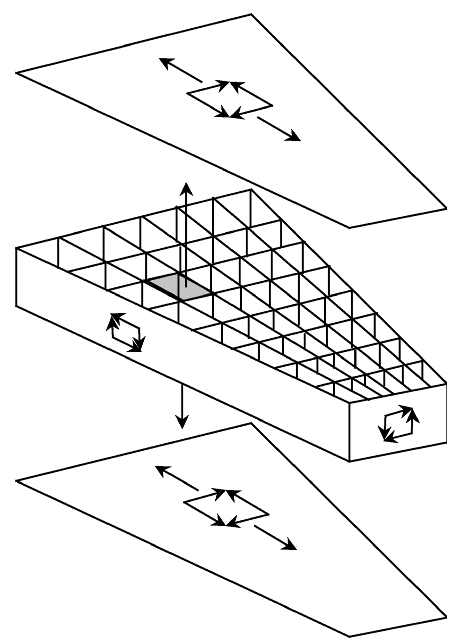

Fig. 5 Final FEM 1 model showing upper and lower skin with in-plane normal and shear stiffness and lattice core with out-of-plane normal and controlled directional shear stiffness.

Design 1 (D-1) Results

Spar web concept generation takes place during design 1(D-1) activities. D-1 activities produced four structural concepts that were carried into Design level 2 efforts. The D-1 activities included presentation of the FEM 1 models and generation of FEM 2 concepts. The structural designer presented load path results to project participants in the form of principal shell force vector plots.

The design team discussed spar web concept possibilities and settled on a concept pool comprised of two-, three-, four-, and seven-spar web concepts. Rib design was delayed to the FEM 2/design 2 phase. D-1 meetings provided information about manufacturing constraints on rib design, with manufacturing team members specifying that ribs must be oriented normal to spars, thus removing a design freedom from discussion and analysis.

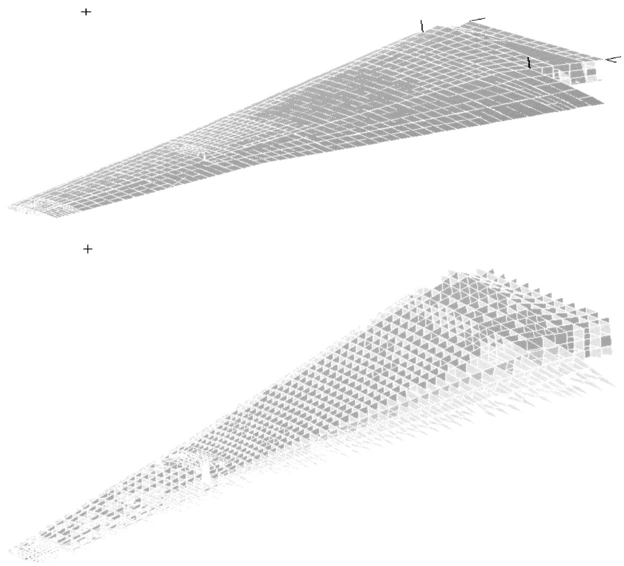

Fig. 6 FEM 1 wing structural model: top, skin; and bottom, internal lattice structure.

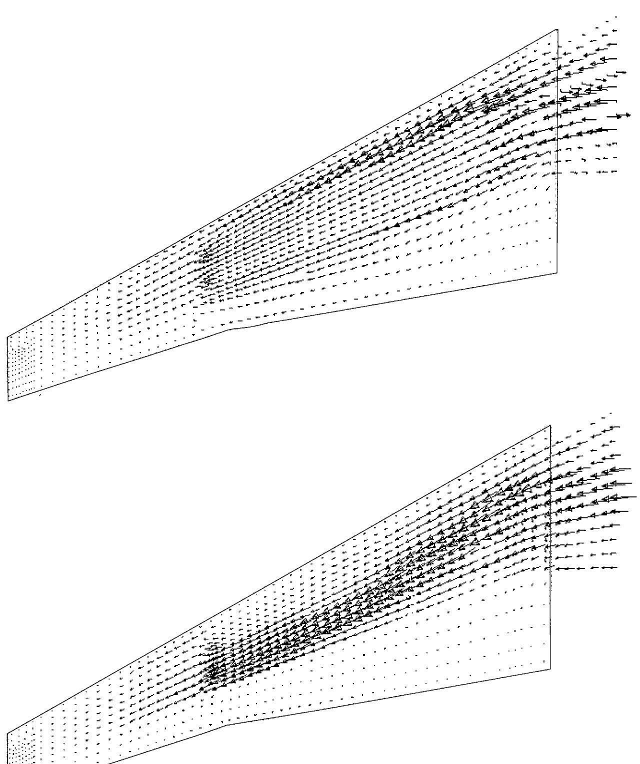

Fig. 7 Maximum/minimum principal shell forces for critical load case 4, positive dynamic gust at V_c-M_c knee: top, lower skin; and bottom, upper skin.

From this initial activity, we concluded that, while interesting, FEM 1 models were not as effective as expected. This was because of at least four factors. First, the accuracy of the FEM 1 model formulation was not yet established, resulting in low confidence levels for the results by the structural designer and other team members. Furthermore, because the wing design problem was not novel (a high-aspect-ratio wing has beam-like behavior, with little advantage given to high fidelity FEM analysis), the structural designer knew from experience where the force flows would be and did not gain new information or insight from the FEM 1 model. A more novel design problem, such as a fuselage or low-aspect-ratio wing, might serve to better demonstrate the utility of FEM 1 models.

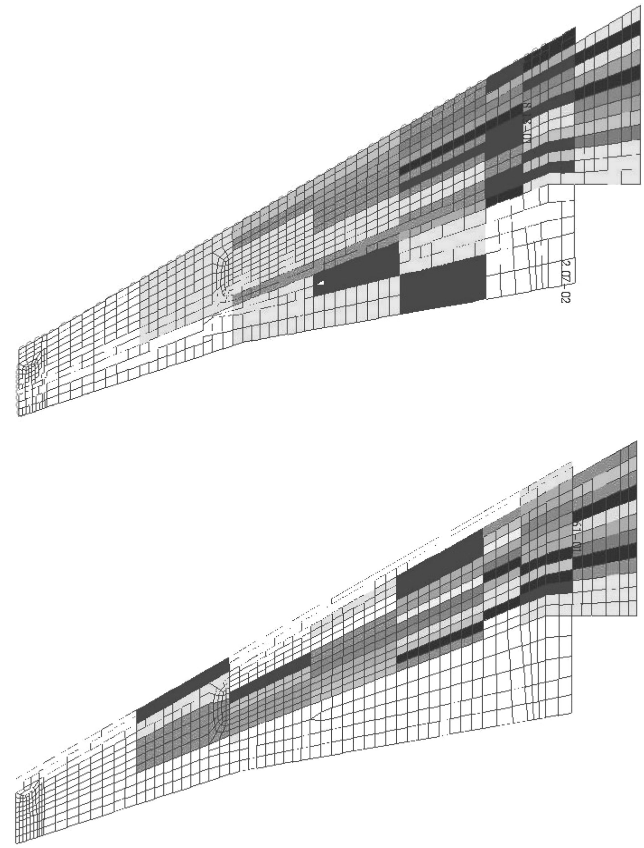

Fig. 8 Skin thicknesses optimized over all load cases: top, lower skin; and bottom, upper skin.

The FEM 1 models would have been more useful at an earlier conceptual design stage, before aerodynamic and performance design maturity, when outer mold line definition could be influenced. Finally, because there was no established relationship between the FEM 1 structural weight calculations and the final wing box weight, FEM 1 model utility was lessened. On the other hand, D-1 began the team communication process, and participants agreed that this early meeting had value.

Phase 2

The goal of phase 2 team activities is to integrate medium-fidelity structural analysis and formal optimization results with the team design decision process. The purpose of the finite element model, FEM 2, used for phase 2 is to provide information to evaluate the spar web concepts generated during design 1. The design 2 activities juxtapose the structural evaluation with nonstructural evaluations (e.g., manufacturing cost estimates) to select a spar web/rib concept through structured selection methods. Design 2 activities generate structural concepts for the next level of structural detail, involving decisions about joining with stiffeners and fasteners. Using FEM-2 information and team meetings, the design team was able to produce a first-order cost evaluation that enabled a relative ranking of costs for each configuration.

Finite Element 2

Although there was only one FEM-1 model, there are several FEM-2 models because D-1 produced several different concepts. The FEM 2 spar design models of concepts developed in the D-1 phase must add buckling, deflection, and manufacturing (minimum gage) constraints to the stress constraints considered in FEM 1. The FEM 2 models include shell elements for skin, ribs, and spar webs, but the same set of loads used by FEM 1.

Ideally, the transition from the FEM-1 model to the FEM-2 models is a seamless evolutionary process with changes to only a few parts of the FEM-1 model, such as replacing the shear core by

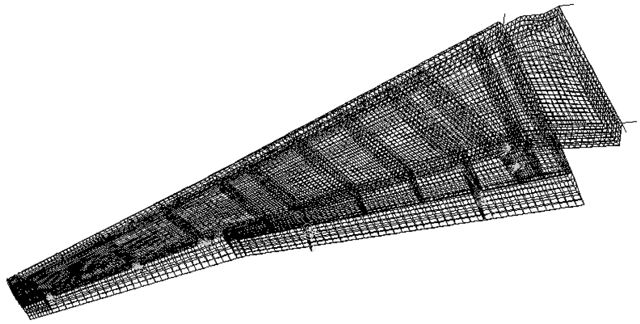

Fig. 9 FEM 2 model for two-spar concept.

rib/spar webs. Figure 9 shows the FEM 2 finite element model for a two-spar concept generated in Design 1.

FEM 2 models also used a NASTRAN-based, modified method of feasible directions optimizer. In addition to using skin thicknesses as design variables, FEM 2 models also add spar web, rib thicknesses, and stringer cross-sectional areas to the list of design variables. The design process experiment produced FEM 2 models produced: stress maps for each load case; buckling eigenvalues and mode shape plot for the maximum bending load case; optimized thickness distribution for skin, spar webs, and ribs; and, optimized structural weight (which was then normalized to FEM 1 weight).

The addition of buckling constraints required high mesh density for accurate solution, necessitating finite element models with upwards of 90,000 degrees of freedom. This caused technical difficulties because optimization solutions consumed large amounts of time and memory, causing delay and problem reformulation. The large number of degrees of freedom can also introduce error in the buckling solution; however, there was no evidence of error with the FEM 2 results.

FEM 3 modeling can revisit the application of buckling constraints and provide additional fidelity and confidence, for the buckling solution. Buckling analyses and optimizations have been effectively and efficiently conducted using much coarser finite element mesh densities, solving a global model for internal loads and transferring these loads to solve the local panel buckling problems. The coarser global model method shifts the time burden from computation to modeling.

Rib design begins with choosing the minimum number of ribs for structural connectivity for flap, aileron, systems, and landing gear. The activity then used the FEM-2 model to perform design trades. The structural designer used his experience to place ribs, solve the optimization problem to determine buckling margins, and moved ribs to bring this margin to the level dictated by design requirements.

Once the structural designer obtained acceptable rib layouts and buckling margins, he then ran the FEM analysis to optimize skin and web thicknesses with stress and buckling constraints to determine minimum weight material distributions. This procedure was followed to optimize rib number and placement for each of the four structural concepts.

Each structural concept model contained seven stringers, whose locations corresponded to possible spar locations. On the seven-spar model, each stringer represented a spar cap. On the two-spar model, two of the stringers represented spar caps and five represented actual stringers. Structural results for the FEM 2 models include stress, buckling, thickness, and weight. Figure 10 shows optimized thickness distribution results from the FEM 2 process for the two-spar concept.

Figure 11 shows optimized weight results for the FEM 2 models normalized to the optimized FEM 1 weight. This figure shows weight results under stress constraints alone and under stress and buckling constraints together. Although FEM predicted structural weight is less than the "as-built" weight, FEM models of equivalent fidelity provide an acceptable basis for relative weight comparison. Figure 11 provides the basis for a structural design decision and demonstrates the effect of constraints on the preferred structural concept.

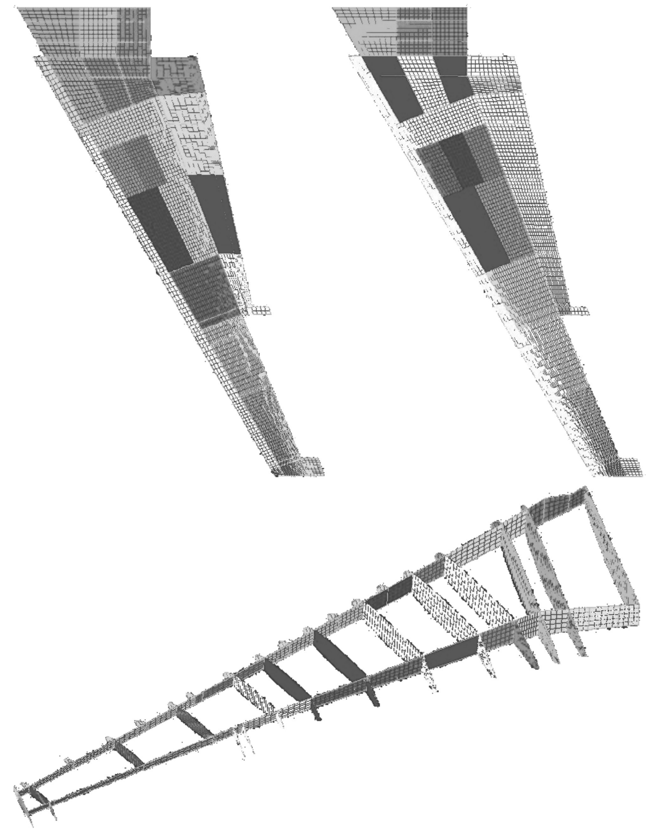

Fig. 10 FEM 2 thickness distribution results for two-spar concept (lower skin, upper skin, rib/spar web).

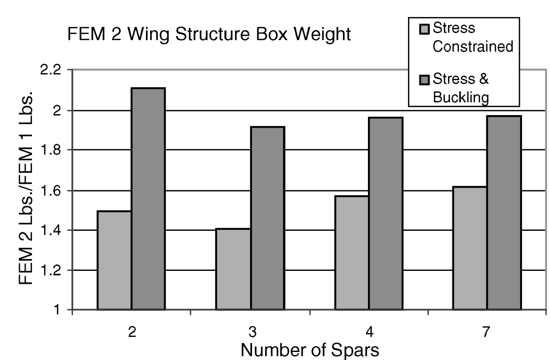

Fig. 11 Weight as a function of spar count for stress only constraint and with buckling constraint.

The FEM 2-level structural definition enabled generation of geometric layouts to address cost, certification, accessibility, and fuel considerations (slosh, volume, and vibration) at a first order of detail. These layouts define concepts for stiffeners, access panels, joints, fasteners, and part counts, providing information for manufacturing cost estimates. All of this information flowed into design 2 activities to support fact-based decision making.

Design 2 (D-2) Activities

The FEM 2 results were presented to the full design team in the design 2 phase. All four concepts satisfied structural constraints such as buckling, stress, and tip deflection. The team evaluated rib/spar web layout concepts against a manageable set of differentiating requirements. Some of these requirements are not the typical constraints a structural analyst/designer would normally consider. These differentiating requirements include objectives such as optimized weight, estimated cost, producibility, maintainability, accessibility, fuel considerations, and certification issues.

Requirements reduction during the D-2 phase does not eliminate the remainder of the requirements from consideration. Those requirements that are analytical must be included in the analytical models at the appropriate level of modeling. Qualitatively evaluated requirements must likewise be evaluated at the appropriate level of modeling. The key to this process is documentation of assumptions about how each requirement will be dealt with in each modeling and design phase.

Scoring Matrix with FEM Structural Information—Results and Observations

At the end of the D-2 phase, a choice must be made. The set of differentiating requirements is a part of a concept selection matrix, discussed by the team and presented in the list of requirements for wing structural design. Table 2 shows this matrix when FEM information was included. Like Table 1, only the categories with weight factors are summed in this table. Other information feeds into the weighted categories.

The matrix and the team activities conducted to construct it clearly show the three- and four-spar structural concepts as preferred choices because the composite scores 3.90 and 3.18 are much larger than either 1.65 and 2.35. The relative difference between the three- and four-spar scores is insignificant compared to the scores of the two- and seven-spar concepts. Although the scores will change if weighting changes, the relative scores are relatively insensitive because even 25% changes in weighting factors still show three- and four-spar as clear winners compared to the other two alternatives.

The design 2 process systematically narrowed the wing structural concept pool to the three- and four-spar structural concepts with buy-in from all team members. These concepts can now be carried forward into FEM 3 and design 3 to allow the next level of structural detail to emerge or an additional decision can be made to reduce the choice to a single concept.

The scoring matrix approach generates more than just a set of numbers. It represents the product of considerable team thought, discussion and, most importantly, team learning. The discussion required for scoring brought the team to consensus and provided a solid foundation for design decisions, superior to decrees or team voting with incomplete information.

The FEM 2 models provided evidence of the effects of stress, buckling, and deflection constraints on the wing weight, enabling rational concept evaluation. Other inputs improved because the FEM 2 model provided the specific structural detail to enable meaningful discussion and evaluation. The structural definition provided by FEM 2 models enabled preliminary design information for access panels, stiffeners, and joints. This geometric configuration then allowed evaluation of manufacturing cost, accessibility, certification, and fuel considerations (volume, slosh, and vibration).

Unlike design 1 activity that required only one meeting, design 2 activities required several meetings. The level of detail included in the FEM 2 models and design 2 requirements required iteration between FEM 2 modeling and design 2 assessment. The team refined initial FEM 2 concepts produced by the structural designer with experiential evaluation and discussions. The final FEM 2 structural models shown in Fig. 9 are the result of significant input from the design team that was then addressed by the designer/analyst.

Design 2/FEM 2 modeling and team interaction led to an evolution of detail throughout the D-2/FEM-2 process. Stiffener concepts emerged from the meetings and became part of the FEM 2 model when it was carried forward into phase 3 with D-3/FEM 3.

Phase 3 Design

The final structural design activity, design 3, selects the structural concept with full detail. Unfortunately, time constraints required that the structural design process experiment conclude after the completion of level 2 activities. Preliminary discussion and modeling for phase 3 activities occurred, but no results or decisions resulted. Phase 3 activities use the remaining design freedoms to optimize and validate the final structural design against all constraints and requirements.

Finite Element 3

The final finite element model, FEM 3, adds structural fidelity to evaluate stiffener concepts and select and develop the full wing structural concept. Objectives for FEM 3 are to generate usable information sufficient to evaluate stiffener layout concepts from design 2 and to determine fastener requirements. FEM 3 detail includes stiffener definition, analytical cost, and producibility models, in addition to using all of the FEM 1 and FEM 2 constraints. Output of FEM 3 exercise will flow into the design 3 selection process for the final structural concept.

The FEM 3 structural model, a portion of which is shown in Fig. 12, consists of a master finite element model and several submodels. The master model contains detail similar to the FEM 2 model, including shell elements for skins, ribs, and spar webs and rod elements for stiffeners. The master model determines global behavior of the structure. Solution of the master model, essentially the updated FEM 2 solution, provides constraints and boundary conditions for each of the submodels.

Dividing the master model into submodels allows more detailed design and analysis. Submodeling enables finer finite element meshing, permits improved definition of design variables, and allows models that can be distributed to others. Design variables for the submodels include the number and dimensions of stringers and caps and the thicknesses of the skin, ribs, and webs. Boundary conditions for these models come from the master model deflection solution at the FEM 2 level. These models also use NASTRAN-based optimization with constraints on stress, buckling, and deflection. The increase in detail at this level justifies, or even demands, improved loads definition, incorporating design definition from previous structural design activities into load calculation and perhaps expanding the load set to include additional special loading conditions.

Table 2 Design 2 concept scoring matrix

Design concerns	Weight factor	2 Spar		3 Spar		4 Spar		7 Spar	
		Raw	Wtd	Raw	Wtd	Raw	Wtd	Raw	Wtd
Weight	0.30	1	0.30	4	1.20	3	0.90	3	0.90
Stiffness	——	1	——	2	——	3	——	4	——
Fuel volume	——	4	——	3	——	2	——	1	——
Cost	0.30	2	0.60	4	1.20	3	0.90	1	0.30
Fabrication	——	4	——	3	——	2	——	1	——
Assembly	——	1	——	2	——	3	——	4	——
Accessibility	0.05	4	0.20	3	0.15	2.5	0.13	1	0.05
Inspection	——	4	——	4	——	2	——	1	——
Maintenance	——	4	——	2	——	3	——	1	——
Fuel considerations	0.05	2	0.10	4	0.20	3	0.15	1	0.05
Certification issues	——	——	——	——	——	——	——	——	——
Fail safe	0.25	1	0.25	4	1.00	4	1.00	4	1.00
Substantiation	0.05	4	0.20	3	0.15	2	0.10	1	0.05
Weighted sum	1.00	——	1.65	——	3.90	——	3.18	——	2.35

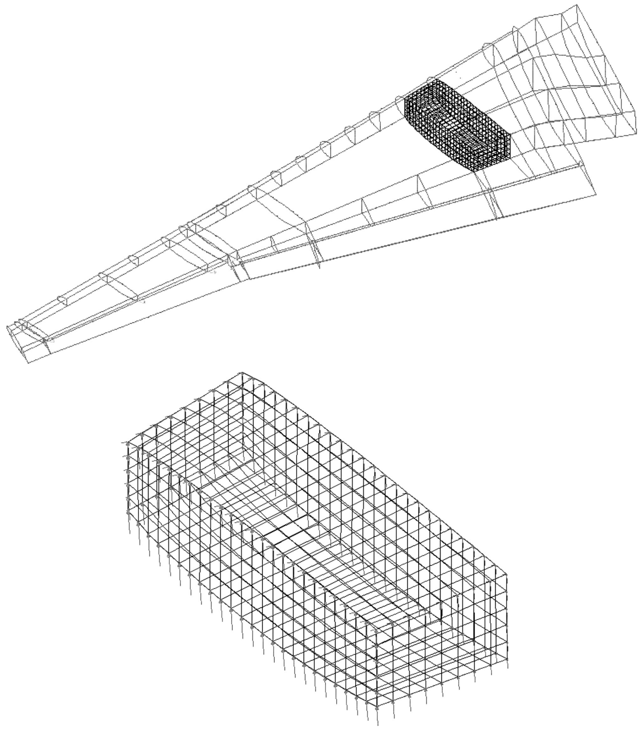

Fig. 12 Example of FEM 3 model.

Design 3

The design 3 process evaluates the structural concepts that address all of the structural and nonstructural requirements and requires an expanded evaluation matrix. The design 3 evaluation matrix will contain the same five distinguishing requirements as the design 2 evaluation matrix. The difference between the original evaluation matrix and the design 3 evaluation matrix lies in the fidelity and quality of the information that goes into them and the nature of the concepts being selected.

The FEM 3 models not only generate improved structural information, but also enable improved geometric definition. This improved geometric definition enables improved cost, certification, fuel, and accessibility evaluations. These evaluations must be of sufficient quality and fidelity to select and define a structural concept that meets the preliminary design phase exit requirements. Structural details for this concept include skin thickness distribution; spar and rib locations; spar; cap and stiffener geometry, size and location; and fastener selection and spacing.

Conclusions

Innovative, effective designs result when the maximum number of design freedoms are considered and then used or eliminated on a rational basis, using the best possible information—including empirical models, relevant designer experience, and analysis. Design degrees of freedom provide opportunities to create superior design, but these freedoms rapidly disappear because of decisions made on an ad hoc basis. When a design freedom is eliminated, it is difficult to reacquire it, even if it is later shown to be valuable. This research has provided a learning experience about the value of conceptual structural design tools, structural design processes, and the interaction between these tools and organizational processes. Improving the balance in the level of structural technology used in preliminary design activities is critical to improving multidisciplinary design team effectiveness.

Formal, structured design process organization for aerospace design provides a powerful, effective approach to use for both ordinary and innovative design when an interdisciplinary team is required. To be effective, structured design needs analytical tools such as finite element methods must be connected to multidisciplinary design team processes as early as possible to improve aircraft design quality and foster innovation.

The design framework comprised of systematic problem definition (i.e., systems engineering requirements management and process definition), and structured solution synthesis (i.e., matrix-based scoring) improves team processes through more effective communication, problem awareness, and team member commitment. These structured design activities help to bring the design team to consensus, strengthening team member commitment.

This approach differs from the traditional analytical method of specifying full detail and constraints in the first structural model, locking in details before design trades can be made and neglecting nonstructural requirements in the analysis until they are identified at a much later time. At the end of the proposed process, the documented evolution of concepts and evaluation enables traceability of design decisions all of the way back to the embryonic, conceptual beginning.

The structural design process formulation and the team experiment described in this paper yielded many valuable insights into the effectiveness of the evolutionary structural design models and the interactions between the technical and organizational design processes. Primary conclusions include the following:

1) The strong interactions that exist between the technical and organizational design processes can be addressed through formal process definition and process design that links analytical tools, information they generate, and the design team.

2) An evolutionary structural design process, aided by finite element methods, helps decision making in the early conceptual design phase.

3) The structural design process must adapt to enterprise needs and will be different for organizations depending on the nature of the product (i.e., the market being served).

The evolutionary structural models, FEM-1 and FEM-2, reduced the technical deficiency of the structural discipline. During the design process, the structural "analyst" was an important concept contributor, not just an analyst. The construction of the FEM-1 and FEM-2 models improved his ability to communicate his needs. However, an undesirable level of technical deficiency was apparent during attempts to assess producibility and to rank concepts for cost. Producibility experts were reluctant to commit support until sufficient detail existed to support their opinions. This understandable reluctance reduced the effectiveness of the team.

The tendency to delay decisions until sufficient detail exists persisted throughout the design experiment in all disciplines. All participants wanted acceptable levels of technical risk before committing their expert opinions to support design decisions. The perception was that additional detail in evaluation models increased the model fidelity, thereby reducing the risk associated with the decision. However, the longer the process goes without decisions, the more unwittingly committed the team becomes to the details being cemented into other member's concepts and evaluation models.

The forces exerted by decision postponement must be countered by team processes that encourage decisions. Quality designs will not result unless design freedom is exploited when it exists. To fully explore the structural design space, structural models must be only sufficiently complex to support informed decisions at the current level of detail. Additional detail must be withheld to prevent the process from stalling or the design from becoming committed to that detail.

Conceptual structural design tools must effectively communicate optimized structural information necessary to make design decisions at appropriate times in the process. If these tools provide structural information too late in the process, they are analysis tools only, not design tools. Future tool development must understand the process it serves and how it can improve that process.

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