
Chapter 1

Introduction

1.1 Structural optimization

The field of structural optimization is broad in both the problems that are addressed and in the methodologies that are used. Haftka & Kamat (1985) and Cohn & Dinovitzer (1994) discuss many of the forms that structural optimization research takes. Due to this broad nature, it is valuable to consider a number of key aspects when categorizing a particular structural optimization application or method. The following two sections aim to provide a general overview of the possible categories for structural optimization applications and methodologies. The aim of these sections is to assist the reader in understanding what sub-fields are relevant to this dissertation. Specific literature reviews are provided in the later chapters for each of the various projects that were undertaken.

1.1.1 Applications

The most fundamental aspect of a structural optimization application is the type of structure being optimized. The applications of structural optimization can loosely be divided into four types of structures - trusses, shells, solids and composites. Truss structures often occur in all areas of engineering that involve structural mechanics and hence have been a focus of much structural optimization research (Falcon & Herskovits, 1998, Hanahara & Tada, 1998). Thin shells include both in-plane deformations (i.e. plane stress) and out-of-plane deformations. Both in-plane and out-of-plane thin shell models are frequently used in aerospace structural analysis and optimization (Livne, 1994, Backlund & Isby, 1988). Solids play important roles in mechanical and geo-technical engineering (Suzuki *et al.*, 1997) and composites frequently appear in aerospace and civil engineering (Manne & Tsai, 1996, Hossain, 1998).

Structural optimization applications can also be classified by how closely they approximate a real world problem. There is a large imbalance between the current possibilities of structural optimization software and its application by practicing engineers (Mücke, 1999). It is important to draw a distinction between the real world and the idealization since real problems can be cast into any number of idealized problems that bear little resemblance to one another. This research aimed to solve problems that were as close to the real world as could be expected within the constraints of academic research. This focus should not be seen as a criticism of the theoretical structural optimization work that has given a rigorous mathematical foundation to the field. Rather, the work presented in this dissertation was aimed at applying the tried and tested theories in new ways and on new problems, with a view to addressing more manufacturing concerns.

Another important aspect of structural optimization applications is the dimensionality of the structure, i.e. 1D, 2D or 3D. Simplification of the problem often involves a reduction in the number of dimensions used. Frequently this reduction allows extra complexity in the problem formulation. However, this comes at the expense of less real-world solutions. In this research, 3D models were used almost exclusively since only these cases can be considered to be true real-world applications.

A fundamental aspect of any structural optimization problem is the choice of design variables. The variables can be continuous (e.g. physical dimensions) or discrete (e.g. material choices). Including too many design variables can lead to overly complex models. However, using too few design variables can limit the diversity of possible solutions, and hence, sacrifice the optimality of the results. In the studies presented within this dissertation, the design variables were carefully chosen to address only the most important objectives of the optimization whilst keeping the models as close to the real world as possible.

Finally, the nature of the topological effects resulting from changes to the design variables is a fundamental attribute of a structural optimization application. That is, whether the optimization acts upon the design's shape, member sizing or freely on its entire topology. This choice has profound implications on the optimization

methodologies that can be applied and the attributes of the results that can be obtained. In this dissertation, topology and sizing optimization are applied in some detail, however shape optimization is not considered.

To better explain the concepts involved in these different types of optimization, Appendix A contains a brief review of the commercial structural optimization software known as GENESIS (by VR&D).

1.1.2 Methods

An important distinction between different structural optimization methods is the use of Finite Element Analysis (FEA). Zienkiewicz (1977) presents a very complete summary of this method that involves finding the solution to a large system of equations relating to the deformation and internal stresses in a structure. To perform an analysis, the structure is decomposed into a large number of finite elements. Within each finite element, shape functions are used to represent the deformations due to applied loads. FEA has become a popular tool for structural optimization since it provides good estimates of structural performance for shapes with complex geometry or geometry that changes during the course of the optimization. Recent increases in computer power have made individual analyses fast enough for hundreds or even thousands to be completed in one day. Within this research, FEA was used extensively due to its strength at modeling real-world structures.

The use of mathematical programming methods is an important factor in classifying a structural optimization method. There are a number of structural optimization methods that utilise mathematical programming techniques (Vanderplaats, 1988). Often, such methods are preferred because they can offer a convergence to a theoretically optimal solution. Methods that do not fall under mathematical programming can generally be classified as heuristic methods. In general, heuristic methods involve mathematical techniques but they do not always allow a proof of optimality. Methods of both types were applied in this research.

Structural optimization methods can also be constrained or unconstrained. Real-world problems are frequently subject to constraints, so constrained optimization was an important aspect of the work presented in this dissertation. In some cases, the problem can be simplified by restating it in an unconstrained manner. This style of optimization also played a role in this research.

1.2 The Cooperative Research Centre for Advanced Composite Structures (CRC-ACS).

The CRC-ACS is Australia's leading research and development organisation in the field of composite structures and materials. It was founded in 1991 by the Australian Government to work in collaboration with major universities, industrial corporations and the Defense Science and Technology Organisation (DSTO). The major research programs of the CRC-ACS involve material science, improving manufacturing processes, improving structural performance, improving operations, technology demonstration and education. A significant motivation behind setting up the CRC-ACS was to provide R&D support to Australia's aerospace manufacturing industry.

The research reported in this dissertation was part of the CRC-ACS efforts into the concurrent design of aerospace composite structures. As such, the structural optimization tasks studied in this work were closely related to the tasks under investigation by the CRC-ACS throughout the same time period. A particular focus of the CRC-ACS work has been on two aircraft components – spoilers and wing ribs. Although, none of the work presented here was applied to actual designs, this research did play a significant role in influencing the research and development activities undertaken by the CRC-ACS.

1.3 Manufacturing Issues in Engineering Design

The most important aims in this research were to understand and to overcome problems that relate to the manufacturing of optimized structures. Hence, this section

discusses the significant issues and recent efforts to overcome them. Efforts by industry to address manufacturing issues often take the form of concurrent engineering and this is discussed in Section 1.3.2. Frequently the driving force behind manufacturing process improvement is increasing the profitability of the manufacturing company. Hence, minimizing the 'manufacturing cost' is often the objective of manufacturing optimization studies. Indeed, the majority of the literature on manufacturing research relates to process modeling and cost estimation. The reader is referred to Chapter 5 of this dissertation for an in-depth review of this literature with a particular focus on composite structures.

1.3.1 Common Issues in Manufacturing

Some common manufacturing concerns are process sequencing, labour cost, part mating, protecting the part during processing, batch size, non-destructive inspection and tooling. Process sequencing is perhaps the most fundamental issue in manufacturing optimization since significant timesaving can be realized through performing processes that utilize common resources in common locations or at common times. The cost of labour is largely dependent on the time taken to manufacture the product, and the required level of operator skill that is required can also be a factor since highly skilled workers are usually more expensive

The mating of the various components of an assembly can be a particularly time consuming activity. Hence, an understanding of the assembly implications of design decisions is important during the early design stages. Furthermore, a general trend during manufacturing optimization is the reduction of the number of components (part count), and hence, the amount of assembly activity. During the assembly stages, the individual components may need to be protected from the physical activities that often involve large forces for joining the parts together. For instance, installation of solid rivets on aircraft panels often requires a temporary protective cover to be placed around the rivet location prior to flattening the rivet head.

Non-destructive inspection is an important final stage in manufacturing since it is the only way of finding out if defects were introduced in the product during

manufacturing. Typical tests for high performance aerospace composites include ultrasound scans to detect flaws in the laminates and dimensioning checks to detect any warping that was introduced during the high temperature curing processes.

1.3.2 Concurrent Engineering

Frequently, the experts on the above-mentioned issues are not design engineers but rather, the work shop personnel who are tasked with performing the various manufacturing processes. This separation of knowledge can introduce difficulties into the design process when decisions are made without a good understanding of their implications. Concurrent engineering is a framework for engineering design that emphasizes a more parallel and integrated approach, whereby a wide range of issues is considered progressively throughout the design process. It recognizes that no single person can understand all the issues relating to design decisions.

A typical design group using a concurrent engineering approach would organize frequent meetings involving people representing many aspects of the product being developed. This team is labeled the Design Build Team (DBT) in the language of concurrent engineering. This may include personnel from the workshop, structural analysis, procurement, marketing, etc. By working in a more team-oriented environment, the designers can produce better designs that are more suitable for manufacturing, inspection, transportation, etc. Hence, concurrent engineering plays a valuable role in engineering design.

1.4 Composites and Other Thin Panel Structures

Due to the nature of its industry partners, the CRC-ACS is predominantly interested in research relating to composite structures for the aerospace industry. A large proportion of the load bearing structure in modern aerospace vehicles is of thin panel nature, i.e. sheet metal or laminated composites. Hence, the aerospace industry is a considerable driver behind many developments in this area.

For laminated composite structures occurring in aerospace applications the mechanical properties are often approximated as quasi-isotropic, allowing modeling with isotropic methods. Hence, the content of this dissertation related to FEA-based structural optimization is not strictly limited to composite structures but can also be applied to truly isotropic thin panel structures such as sheet metal structures or injection moulded plastics. These thin panel structures have unique mechanical behaviour and manufacturing considerations that are discussed in the following sections.

1.4.1 Mechanical Behaviour

When loaded in compression or shear, thin panel structures are prone to buckle with out-of-plane deformations. Hence stiffening (often with other thin panels) is often necessary. The inclusion of stiffeners in a design can dramatically effect the complexity and time taken for structural analysis and optimization since each stiffener must be considered individually. Simplified ‘smearing’ approaches can be employed when the stiffeners are uniformly distributed and closely spaced. However, this is often not the case in real-world aerospace designs. Additionally, analysis complications can arise for high performance fiber reinforced composite materials such as CFRP since failure modes are often coupled to both the local material properties and the global structural behaviour. In these cases, complex non-linear FEA is required.

1.4.2 Manufacturing

The inclusion of stiffeners can also add significant complexity to the manufacturing processes for a particular design. In the simplest cases, mechanical fastening is required to join the stiffeners to the base part. Design for manufacturing of such structures is relatively straightforward since the extra costs associated with the mechanical fastening are relatively easy to estimate and are largely de-coupled from the rest of the manufacturing processes. However, high-performance composite

structures frequently seen in aerospace applications often utilize co-cured, integral stiffeners (Lawrence, 1993 and Sanders *et al.*, 1996). In these cases, the costs associated with different manufacturing decisions are not well understood at the outset of the design process. One main source of manufacturing complexity for complex composite structures is the mould used for curing the structure. To ensure that a stiffened part can be extracted from the mould, extensive testing and re-design of the mold may be needed. Other sources of complexity include limited access to narrow regions of the structure, complex mould flow behaviour around the stiffeners and alignment of parts that have undergone thermal expansions.

1.5 Research scope

The scope of this research project was primarily influenced by the goals of the CRC-ACS and related to the development of methodologies to more effectively optimize thin-panel structures. An emphasis was placed on the constraints and costs involved in manufacturing high performance composites. Due to the CRC-ACS involvement with prominent aerospace manufacturers in Australia, the structures that were the subject of this research were either of a type seen in aircraft or had similar attributes to such structures.

An investigation into the capabilities and limitations of existing commercial and non-commercial software relating to the above issues was a significant activity. Also, a number of new software programs were created to more clearly demonstrate the original contributions of this work and to implement various novel methodologies that were developed. The two categories of software that were most relevant to this research were structural optimization software and CAD modeling software since practically all of the specialist software required for composite structural design is of one of these types.

1.6 Thesis layout

The work presented in this thesis has been divided into three areas. Firstly, the relatively mature field of structural optimization was examined to see how existing methods could be better applied to problems involving manufacturing issues. Secondly, methods were developed for modeling and optimizing the manufacturing of composite structures. Finally, a new framework for integrating manufacturing concerns into a concurrent engineering environment was proposed and tested.

Chapter 2 is a detailed investigation of brick-based 3D topology optimization for an enclosed thin-panel structure. A generic aircraft spoiler was optimized with a recently introduced algorithm. In keeping with the main theme of this work, every effort was made to address manufacturing issues during the topology optimization. A novel method for determining the optimal interior structural arrangement of enclosed, near-flat structures like aircraft control surfaces is presented. A custom approach to display this data was used. With the assistance from this approach, three new metrics were introduced to quantify and compare the manufacturing costs of various enclosed thin panel topologies.

In Chapter 3, a topology optimization case study for a stiffened thin shell structure is presented. A plastic milk crate subjected to buckling and linear static loading was investigated. This research introduced a new way to optimize the 3D shape of stiffened, injection moulded, plastic products. Also, a simplified way to improve the buckling performance of structures with a linear static FEA solver was demonstrated.

Chapter 4 investigates the use of parametric sizing optimization in conceptual design by revisiting the generic aircraft spoiler design problem from Chapter 2. A FEA modeling strategy for arbitrary internal structural configurations was automated in ANSYS. Various spoiler configurations were studied and each one was optimized for minimum weight under deflection and buckling constraints. Observations about the weight and manufacturing complexity of the different configurations were made.

Chapter 5 contains a review of a manufacturing process modeling database that is under study by the CRC-ACS. Subsequently, a novel approach using a Feature-Based

philosophy for the determination of manufacturing process steps is presented. A new software program named Process Link was created to streamline the creation of manufacturing process models from geometric data. The automatic creation of manufacturing features was demonstrated with a spoiler example

Chapter 6 begins with a discussion on the interfacing issues of CAE software. It also contains a discussion of data sharing issues in engineering design and explains the ISO project known as STEP. Recent developments in the areas of Feature-Based and Knowledge-Based methods are discussed and a new approach for integrated concurrent optimization of composite structures using Knowledge-Based methods and STEP data structures was suggested.

From the approach suggested in Chapter 6, a prototype Knowledge-Based system for composite structural optimization was developed. In Chapter 7 this system is applied to a generic design task. A Knowledge-Based concurrent engineering model for composite wing ribs was derived. In this model, manufacturing issues were integrated with structural analysis and optimization models, and the design for a specific rib was optimized.

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