Chapter 1

Introduction

1.1 Motivation

In conventional aircraft and aerospace applications it has been common practice to design plate and shell structures, such as fuselage and stabilizer panels, to buckle at load levels below their design ultimate load, thus exploiting the postbuckling strength of these structural components. Although advanced composites have a significant advantage over metals in specific strength and stiffness, composite structures, may be heavier than their metallic counterparts if they cannot be designed to operate in the postbuckling load regime. While thick isotropic or composite plates under in-plane load generally fail at load levels below or in the vicinity of their buckling load, failure of thin flexible plates generally occurs far beyond the buckling load. If a plate fails far before its buckling load is achieved, potentially its weight can be reduced by reducing its thickness, thus its weight, without jeopardizing its load carrying capability. If, on the other hand, the thickness of the plate is too small, then the plate starts experiencing substantial out of-plane deformations upon loading. This type of deformation results in softening of the plate in the applied load direction. However, if the edges of the plate are properly supported, this softening does not cause the plate to lose its load carrying capability. Such plates are referred to have postbuckling strength. To compete on a weight-efficiency basis, therefore, thin composite panels must be designed to function under postbuckling conditions.

As was the case for simple plates with supported edges, compressively loaded stiffened panels can exhibit considerable postbuckling strength. Upon buckling, the behavior of stiffened panels can be classified into three general types: Local postbuckling, global (Euler) postbuckling, and an interaction between local and global modes termed modal interaction. The response of a perfect panel for each type is shown by the solid lines in Figure (1.1). For local postbuckling, where the panel generally buckles into half-wave lengths about equal to the width between the stiffeners, the panel possesses postbuckling strength, carrying loads greater than its buckling load. For global postbuckling, where the panel buckles into one half-wave length along its length, the panel's load carrying capabilities remain essentially neutral after buckling. For modal interaction, where the local and global modes have critical loads of almost equal value, the panel is not able to carry loads greater than its buckling load.

It is also well known that the panels considered in this study possess the unfortunate property of being highly sensitive to geometrical imperfections and that the elastic limit load (the bifurcation buckling load) of a panel is greatly affected by the initial imperfections in the panel shape [2], see Figure (1.1). Engineers are accustomed to using empirical "knockdown factors" in order to accommodate the large discrepancy between theoretical and experimental values of buckling and elastic limit loads. The knockdown factor, when multiplied by the classical buckling load for the perfect structure, yields an estimated lower bound of the bifurcation buckling load for the imperfect panel. Knockdown factors are often adopted as the lower bound of the buckling loads obtained experimentally for a range of distinct structures, materials and manufacturing processes. Such an approach has several drawbacks. It would seem that the estimates should constantly be updated to include new experimental results. Furthermore, this approach mixes panels produced by rough manufacturing procedures (and therefore associated with a greater reduction of the buckling loads) with those produced by more refined techniques (and hence buckles at higher loads). This implies that the design of panels with low initial imperfections may be overly conservative.

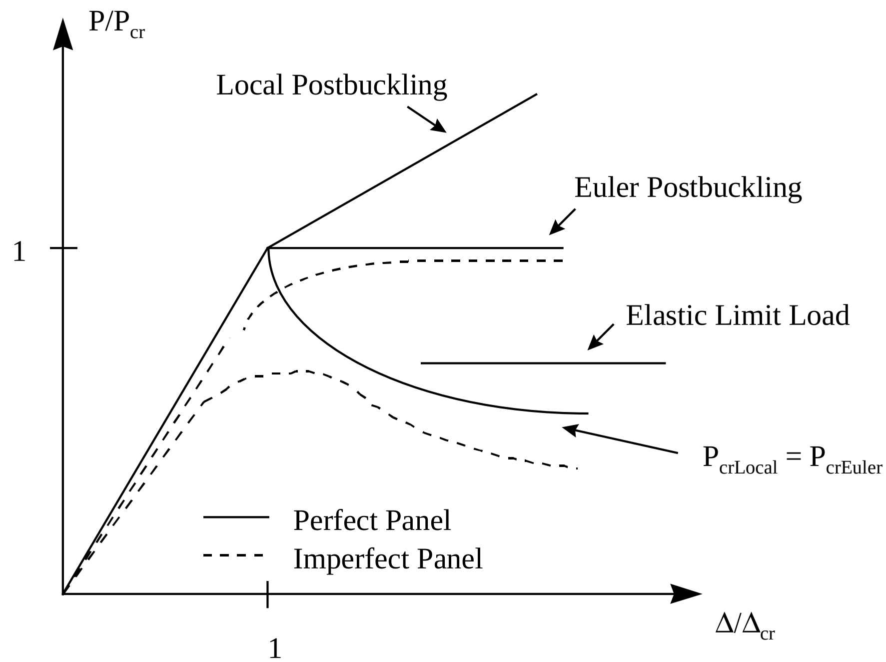

Figure (1.1) Nonlinear elastic behavior of stiffened panels

The main objective of this study is to introduce a new scheme for the design of thin composite stiffened panels that includes manufacturing and uncertainty information about the geometric imperfections. The basic idea is to try to include as much information about the manufacturing and uncertainty variables as possible in the early design stages of these panels thus producing more realistic designs. It is also suspected that there is a direct relationship between the different design parameters (e.g. stacking sequence) and the imperfection profile resulting in the panel after curing. Relating the manufacturing process to the design optimization should enable us to study the existence of such a relationship and its implications. A tool that accounts for such a relationship could improve designs significantly.

1.2 Literature Review

In this section, previous investigations on postbuckling analysis, convex models, composite manufacturing models and the optimum design of stiffened composite panels are discussed, along with a brief introduction of the present approaches to these topics.

1.2.1 Geometrically Nonlinear Finite Element Analysis

The first work on the extension of the finite element procedure to geometrically nonlinear structures was reported by Turner et al [3]. A linearized incremental analysis procedure was described and tangent stiffness matrices presented for a stringer (axial force element) and a triangular membrane element. Since bending was not included, their approach is restricted to investigating instability resulting only from unstable modal configurations.

In a subsequent paper, Gallagher and Padlog [4] outlined a consistent procedure, based on the Principle of Minimum Potential Energy, for introducing geometric nonlinearity in the displacement based finite element method. Their formulation is restricted to stability analysis in which the response prior to buckling (bifurcation) is linear. This assumption is introduced by neglecting the nonlinear rotational terms in the strain-displacement relations prior to buckling. They also derived a linearized tangent stiffness matrix for a beam-column element.

Linear buckling of beams, membranes and plates has since been studied extensively [5-14]. A linearized stability analysis is convenient from a mathematical viewpoint but quite restrictive in practical applications. What is needed is a capability for determining the nonlinear load-deflection behavior of a structure. Considerable effort has also been expended on this problem and two approaches have evolved: Class-I methods which are incremental in nature and do not necessarily satisfy equilibrium; and class-II methods which are self-correcting and tend to stay on the true equilibrium path.

Historically, class I was the first finite element approach to solving geometrically nonlinear problems [3,7]. In this method the load is applied as a sequence of sufficiently small increments so that the structure can be assumed to respond linearly during each increment. For each increment of load, increments of displacements and corresponding increments of stress and strain are computed. These incremental quantities are used to compute various corrective stiffness matrices (variously termed geometric, initial stress, and initial strain matrices) which serve to take into account the deformed geometry of the structure. A subsequent increment of load is applied and the process is continued until the desired number of load increments has been applied. The net effect is to solve a sequence of linear problems wherein the stiffness properties are recomputed based on the current geometry prior to each load increment. The solution procedure takes the following mathematical form

$$[K + K_I]_{i-1}\{\Delta q\}_i = \{\Delta Q\} \tag{1.1}$$

where $[K]$ is the linear stiffness matrix, $[K_I]$ is an incremental stiffness matrix based upon displacements at load step $i-1$, $\{\Delta q\}$ is the increment of displacement due to the i^{th} load increment, and $\{\Delta Q\}$ is the increment of load applied. The correct form of the incremental stiffness matrix has been a point of some controversy. Marcal [15] separates $[K_I]$ into initial stress and displacement matrices but neglects quadratic terms of the initial displacements. Reference [16] on the other hand includes these higher order terms. Murray and Wilson [17] present yet another form of the incremental approach.

The incremental approach is quite popular (this is the procedure applied in this study). This is due to the ease with which the procedure may be applied and the almost guaranteed convergence if small enough load increments are used. However, the procedure has a serious disadvantage in that no real estimate of the solution accuracy is known since, in general, equilibrium is not satisfied at any given load level. This is evident by the drifting of the solution from the true solution. Recourse must be made to solving repeatedly the same problem with successively smaller load increments until convergence of two successive solutions can be established. In addition, for structures requiring many degrees of freedom, the updating of the incremental stiffness matrix plus the inversion of the new coefficient matrix at each load step may become excessively time consuming.

In another class-I type procedure, Thompson and Walker [18] have applied the perturbation method to nonlinear problems. In this procedure, the incremental displacements are expanded in a Taylor series with respect to some incremental load parameter and about some known or assumed equilibrium state. Equations are obtained in the form

$$\{q\}_{i+1} = \{q\}_i + \{\dot{\Delta} q\}_i \Delta \overline{P} + \frac{1}{2}\{\ddot{\Delta} q\}_i \Delta \overline{P}^{\,2} + \cdots \qquad (1.2)$$

where the dot denotes the derivative with respect to the load parameter, $\overline{P}$, and i denotes the load increment index. Vectors $\{\dot{\Delta} q\}, \{\ddot{\Delta} q\}$, etc., are commonly referred to as the path derivatives. The terms in the Taylor series are obtained through the solution of several sets of linear equations equal to the number of terms retained in the expansion. Once the displacements are obtained at a particular load value, the whole process is repeated to obtain the displacements at the next load value. The procedure may of course drift from the true solution since errors will tend to accumulate. The amount of drift is dependent upon the load step size and the number of terms retained in the expansion. The procedure is straightforward but may become time consuming because of the numerous evaluations of the path derivatives. This method is also limited to problems wherein nonlinearities are not too large. Further development of this method is described in Refs. [19,20].

A final class-I type procedure is the initial-value formulation [21-25]. This approach again treats the displacements and loads as a function of some load parameter

$\overline{P}$, such that $\{Q\} = \overline{P}\{\overline{Q}\}$. By differentiating the equilibrium equations with respect to $\overline{P}$, a set of differential equations is obtained in the form

$$[\overline{K}]\{dq / d\overline{P}\} = \{\overline{Q}\} \tag{1.3}$$

where $[\overline{K}]$ is a nonlinear stiffness matrix dependent upon displacements, $\{q\}$, and $\{\overline{Q}\}$ is a vector of scaled or normalized generalized forces. Values of $\{q\}$ at any load $\overline{P}$ can be obtained by numerical integration from a known initial displacement state. If the simple Euler method is used for the integration, then the incremental approach given by Equation (1.1) is obtained. More accurate integration schemes such as the Runge-Kutte method or the predictor-corrector method may be used to reduce the drifting effect, which is so prominent with the Euler integration.

The remaining solution techniques appear to be of class-II type. All these procedures use some method by which equilibrium is assured at any given point on the load displacement curve. These procedures are perhaps best described as self-correcting.

The iterational approach (class-II) to solving the governing nonlinear algebraic equations has been used by many investigators [26-28]. This approach is relatively simple to apply. Starting with an initial estimate to the displacement solution, the nonlinear effects are estimated and a set of linearized equations is solved to obtain an improved solution. This solution is back-substituted into the equations and the iteration continued until convergence of successive iterations is obtained. The success of the method depends to a large extent upon the accuracy of the initial estimate of the displacements. The load may be applied in increments and various extrapolation procedures may be utilized to obtain accurate estimates. Relaxation schemes [27,29,30] may be used to accelerate convergence. While the iterational method is extremely fast from a computational standpoint, it has a serious disadvantage in that it will converge only for moderately nonlinear problems [21].

In order to obtain convergence for problems exhibiting high nonlinearity, many investigators have utilized the Newton-Raphson iterational approach. This procedure is extremely accurate and usually converges quite rapidly for realistic initial estimates of the solution. Its primary drawback is the excessive computational effort required to form the stiffness matrix and invert it at each iterational cycle. Most investigators [21,31-33] now use a modified Newton-Raphson procedure wherein the stiffness matrix is held constant for a number of iterations and then updated after the convergence rate has begun to deteriorate. Again, various extrapolation and relaxation procedures can be incorporated into the iterational cycle to insure and accelerate convergence [21].

More recently, self-correcting forms of the incremental stiffness procedure have been developed by a number of investigators. References [34] and [35] describe combined procedures wherein the incremental stiffness procedure is used for a certain number of load steps and then equilibrium is corrected for by applying Newton-Raphson iteration. Murray and Wilson [17] determine the unbalance in nodal forces at the end of a load increment and then use an iterational approach to reduce the unbalance to zero. Their procedure is essentially a modified Newton-Raphson approach. References [21] and [36] formulate the incremental equations so that the out-of-balance in the equilibrium forces is explicitly taken into account. The resulting self-correcting incremental procedure has the advantage in that it is as easy to apply as the standard incremental procedure but is much more accurate.

1.2.2 Cure Simulation and Process-Induced Deformation in Thermosetting Composites

A fundamental understanding of the relationships between the design parameters, (e.g. laminate stacking sequence) and the overall quality and in-service performance of thermosetting composite structures is needed. The development of residual displacements, for example is strongly influenced by processing history. The autoclave curing process of thermosetting composites has been the subject of numerous investigations [37] to [42]. From early efforts to fabricate composites, various undesirable effects were encountered that lead to poor part quality. Consequently most studies have sought to understand the curing process on a fundamental level. Studies of the curing process have focused on the thermal and chemical interactions, degree of cure profiles, viscosity behavior, void formation and growth, and resin flow phenomena occurring in the composite under the application of a specified temperature and pressure cure cycle history [37,43,44]. Other investigators are more empirically oriented citing general experiences encountered in the fabrication and manufacture of thick-section thermoset composite parts [45,46]. A review of some of the literature associated with the processing of thermosetting composites is now presented.

Early investigations by Levitsky and Shaffer [47] focused on temperature and degree of cure gradients that develop in chemically reacting isotropic systems. Their one-dimensional analytical solution with prescribed temperature boundary conditions enabled them to investigate the influence of various reaction kinetic variables on the curing process. They extended their work to show the significant influence of temperature and degree of cure gradients on the development of stress in isotropic materials induced by non-uniform curing [48-50].

Loos and Springer [38] developed a comprehensive one-dimensional simulation model to describe the curing process of flat unidirectional AS4/3501-6 graphite/epoxy composite laminated plates. The model integrated submodels which describe the fundamental mechanisms associated with the curing process such as the thermo-chemical interactions, resin flow, and void formation. Governing equations describing the curing process are solved with an implicit finite difference method. Temperature, degree of cure, resin flow, and void size, among other processing variables, are predicted as a function of the autoclave pressure and temperature cure cycle history. Experimental verification of the model was performed and results were in good agreement with simulated predictions. This model is extended in this study for the prediction of process-induced deformations.

Kays [37] has conducted a comprehensive three year investigation on the processing issues unique to large area thick-section laminates. The baseline material system was unidirectional AS4/3501 graphite/epoxy. Cure simulation models were developed and used in the investigation. Various autoclave procedures, cure monitoring and non-destructive evaluation (NDE) techniques for thick-section laminates where developed and evaluated. Contributions towards the development of a generic methodology for processing thick-section laminates were made. Developments of microcracks and delamination under certain processing conditions were reported in this study, indicating the importance of processing on the cure and performance of thick-section composites. Although ply-drop geometries were included in the study, cure simulation was limited to a one-dimensional through-the-thickness analysis.

Efforts to optimize cure cycles for the large scale manufacture of thermosetting resin composites have been attempted in Refs. [39,41,42]. Computer-aided curing systems utilizing cure simulation submodels and control feedback systems, were developed. The studies focused on reducing composite manufacturing cost while improving part quality on a reproducible basis.

Bogetti and Gillespie [51] recently conducted a fundamental study of process-induced residual stress and deformation in the thick-section thermosetting composites. A one-dimensional cure simulation model was coupled to an incremental stress analysis. A constitutive model was proposed to describe the material behavior during cure that included chemical hardening, thermal and cure shrinkage effects. This incremental model is used in this study along with the one-dimensional model suggested by Loos and Springer [38] in order to predict the final cured laminate profile.

1.2.3 Convexity and Uncertainty

The probabilistic approach to the modeling of uncertainty begins by defining a space of events and a probability measure on that space. The space is all-inclusive; everything that could occur, and also possibly events that cannot occur, are included. The probability measure contains all information concerning the relative frequency of different events.

The set-theoretic approach to the modeling of uncertainty is different. A space of conceivable events is defined, as in the probabilistic approach. However, no probability measure is defined. Rather, sets of allowed events are specified, and the structure of these sets is chosen to reflect available information on what events can and cannot occur [52].

As a simple example, consider the geometrical imperfections of a composite plate. The imperfection profile of a composite plate ranges from fairly smooth and regular ridges to highly convoluted and uneven distortions. The space of possible shapes is the set of all two-dimensional surfaces with no self-intersections. The probabilistic approach to modeling the uncertainty in the panel shape is to define a function on the set of possible shapes, which gives the probability density for each particular shape. By assuming a Gaussian model for the plate imperfections, the probability density can be related to a correlation function of the surface imperfections. Alternatively, the probabilistic approach may define a probability density function whose argument is a vector containing a finite number of spatial dimensions or other parameters of the panel shape. The set-theoretic approach is to define subsets of the space of possible shapes. The structure of the sets of allowed shapes will represent information on the range of shapes which occur. A family of sets can be constructed to represent different degrees of variation of shape, in connection with various constraints such as age, manufacturing conditions, material, etc. Likewise different classes of sets can be formulated to represent different types of information on the allowed shapes. For example, a simplistic model supposes that the geometrical imperfections of the panel surface vary arbitrarily between lower and upper bounds. A more sophisticated model may include information on variation of both the displacement and the curvature of the surface.

The aim of Chapter 5 of this study is to exploit fragmentary information (which is usually what is available) about the initial imperfection of composite panels, in order to determine the failure load which may be expected. Explicitly, the failure load will be determined as a function of parameters which characterize the range of possible imperfection profiles of the panel. Non-probabilistic convex models of uncertainty in the initial imperfections will be employed. This means that an infinite set of initial profiles will be adopted on the basis of available data (obtained from the manufacturing model in Chapter 4) and then the minimum of the failure load on this set will be sought.

The range of variation of the initial imperfection profiles will be modeled in terms of the variability of the modal amplitudes of those profiles. The N most significant modal amplitudes are assumed to fall in an ellipsoidal set in N-dimensional Euclidean space. The minimum failure load is then evaluated as a function of the shape of the ellipsoid.

1.2.4 Optimization of Composite Stiffened Panels Using Genetic Algorithms

With the incorporation of composite materials into the structural design, the complexity of the design process was greatly increased compared to designing using metallic materials. The variability of ply thickness and orientations added a significant increase in the design space and thus prohibited the use of general design rules as was done with metallic structures designs. In 1976, the general-purpose, buckling analysis code VIPASA [53,54] was released. The analysis considers prismatic structures that are assembled by rigidly connecting thin plate-strips together along their longitudinal edges. The plate-strips are symmetric, balanced laminates and simply-supported along their ends. The analysis calculates the buckling load and mode for any given half-wavelength number, in the context that the plate equations satisfy the Kirchoff-Love assumptions and the panel ends are simply supported.

VIPASA was soon incorporated into the design code PASCO [55,56], which uses the optimization code, CONMIN [57]. PASCO finds the minimum-weight design of stiffened composite panels subjected to buckling and material constraints. Possible design variables include the plate dimensions, ply thicknesses, and ply orientations. Extensive studies comparing PASCO optimum designs with those of EAL [58] and STAGSC-1 [59,60] finite element codes were performed by Stroud et al. [61]. Although a general buckling design code like PASCO has many advantages, there are also drawbacks to this design approach. The PASCO design process usually leads to configurations which have more than one critical buckling mode, result common to buckling critical designs. The optimizer forces the panel to have equal resistance to failure modes, in this case the global buckling mode and the local buckling mode. In the presence of geometric imperfections, this design would likely fail well below the buckling load.

With the understanding that nonlinear effects must be included in the design of stiffened structures and the realization that composite stiffened panels possess significant postbuckling strength [62], attention shifted to developing approximate analyses that incorporate geometric nonlinearities. Lockheed-Georgia Company [63-65] through the sponsorship of the NASA Langely Research Center, developed a preliminary design tool called POSTOP (Postbuckled Open-Stiffener Optimum Panels). POSTOP minimizes the weight of symmetrically laminated composite panels with open cross-section stiffeners loaded into the postbuckling range by a combination of inplane biaxial compression, tension, or shear. Initial bow type eccentricities are considered along with pressure and thermal effects. The approach taken to analyze the nonlinear response of the panel was to decompose the problem into separate postbuckling problems using beam-column theory [66]. The skin section is treated as a long simply supported plate with restraints added along its long edges due to the stiffeners. The stiffeners are analyzed as an assembly of plate-strips to determine extensional, bending, torsional, and warping stiffnesses. The skin section is allowed to reach postbuckled state, however, the local buckling of the stiffener is treated as a failure mode. Design variables include stiffener plate widths, stiffener spacing and ply thicknesses.

The work of Bushnell over the years led to the introduction of PANDA2 [67,68]; a code for the minimum-weight design of laminated composite flat or curved cylindrical panels or shells with stiffeners in one or two orthogonal directions. Initial bow-type eccentricities as well as local imperfections in the form of the local buckling mode is considered.

More recently, Perry and Gürdal introduced NLPANOPT [1], a combination of a finite strip analysis code developed by Stoll [2] and a general-purpose optimization program ADS [69]. Extensive comparisons between the design obtained from PASCO and those obtained by using NLPANOPT are presented in [1]. Imperfection sensitivity studies were also performed on different design cases.

In this study an in-house nonlinear finite element code is combined with a genetic algorithm optimizer developed by Soremekun and Gürdal [70] to get a minimum weight design tool called FEPAD (Finite Element Panel Analysis and Design). GAs (Genetic Algorithms) are probabilistic algorithms that utilize the processes of natural selection by mimicking the concept of survival of the fittest. It has been established that stacking sequence design of composite laminates requires discrete programming since ply thicknesses and orientation angles are restricted to a discrete set of values. This restriction is due to manufacturing limitations because plies are fabricated at certain thickness values. Furthermore, a majority of composite structures are still manually constructed and it is often too difficult to accurately hand-lay plies at odd orientation angles.

In recent years, genetic algorithms have been successfully applied to large, non-convex, integer programming problems, see for example Hajela [71] and Rao et al. [72]. Thus it was obvious that GAs would be well suited for the design and optimization of laminated composite panels. Early works include Callahan [73] who used GAs for stacking sequence optimization of composite plates, and Nagendra [74-76] who did extensive research work with GAs and stiffened composite panels.

1.3 Organization

First a 4-node, 6-degree-of-freedom per node flat rectangular shell finite element is developed for the nonlinear analysis of thin composite panels with geometric imperfections. Using a nonlinear finite element analysis enables us to study a large set of different boundary conditions in addition to the capability of dealing with any material, geometric, or load discontinuity that we might want to consider. A new hybrid integration scheme was introduced in the finite element formulation in order to reduce the finite element analysis cost. The program (Finite Element Panel Analysis and Design – FEPAD) is also capable of performing static, linear buckling, and free vibration analysis of composite structures.

Next, FEPAD was linked with a genetic algorithm discrete optimization code. Genetic algorithms use techniques derived from biology, and rely on the application of Darwin's principle of survival of the fittest. Genetic algorithms are well known for their robustness and ability to search complex and noisy search spaces, which are frequently encountered in the design of stiffened composite panels. A more detailed description of the genetic algorithms and their suitability for composite panels' design is given in Chapter 3 of this dissertation.

In Chapter 4 a simulation program for the autoclave curing of epoxy matrix composites is presented. The objective of such a model is to predict the cured panel profile knowing the material and manufacturing parameters. Tolerances in the material parameters (resin density, resin coefficient of thermal expansion,…) are assumed to be the major source of geometric imperfections in the cured panel. Such tolerances are modeled using spatially varying random numbers and normal Gaussian distributions. The final output of this model is a set of parameters defining the family of panels to be expected from the specific manufacturing process when applied to a given panel design.

In Chapter 5 a convex model for the uncertainty in the geometric imperfections is introduced. Knowing the parameters defining the family of panels to be expected from the manufacturing process, the Convex Model is capable of determining the weakest panel in this set along with its failure load with a minimum number of analyses required.

Finally, the three components of the design loop are combined together in Chapter 6. Figure (1.2) shows the two intermediate design schemes along with the final closed loop scheme. It is clear that the closed loop scheme allows the incorporation of manufacturing and uncertainty information early in the design process. This new design methodology is expected to result in more realistic panels that possess a better chance of satisfying the design requirements in the real world. In other words, minimizing the sensitivity of the design to the geometric imperfections leads to more reliable and realistic designs.

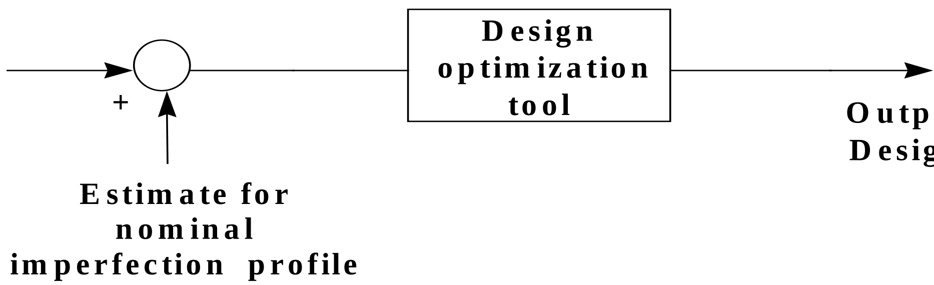

Figure (1.2a) Existing geometric imperfections treatment

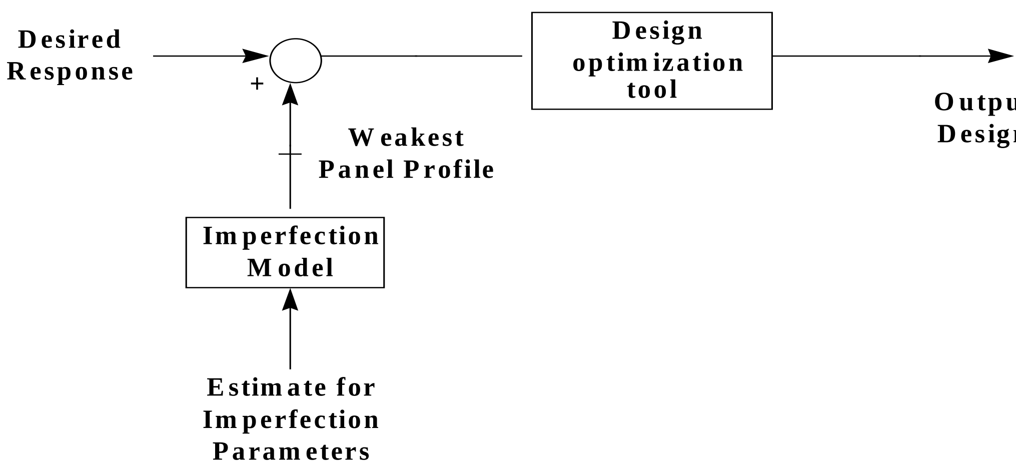

Figure (1.2b) Design process with imperfection model for uncertainties

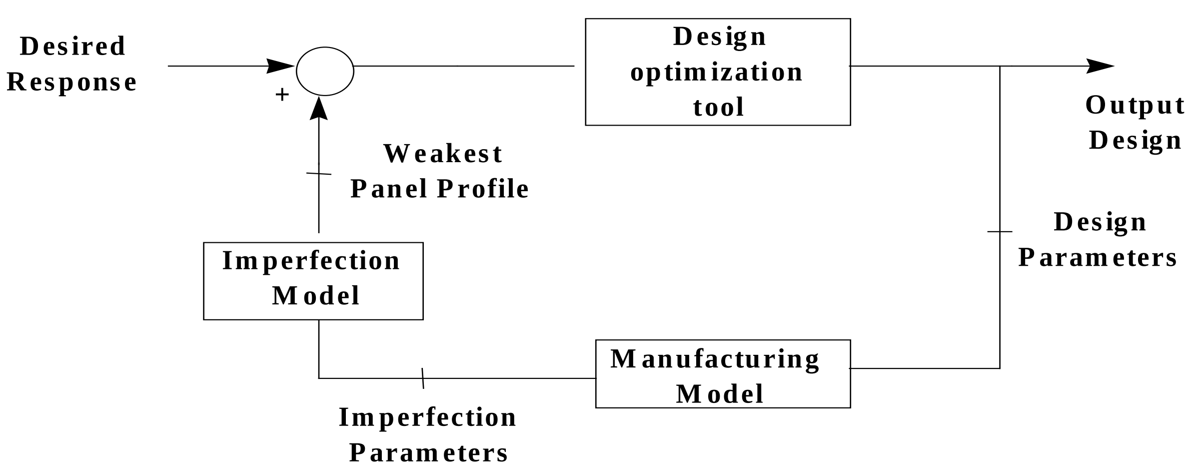

Figure (1.2c) Projected closed loop design scheme