Chapter 6

Results and Discussion

In the previous chapters of this dissertation, we presented four tools the analysis, design, and manufacturing of stiffened composite panels. In Chapter 2, a nonlinear finite element code was introduced for the nonlinear postbuckling analysis of thin-walled stiffened composite panels. Next, the nonlinear finite element analysis code was linked to a genetic optimization code resulting in an optimization design tool for postbuckling response (FEPAD). In Chapter 4, a manufacturing model was presented and randomness in the primitive material parameters was introduced as source of imperfections. The output of this manufacturing model is a set of imperfection profiles that correspond to the specific design under consideration in the simulation. Finally, Chapter 5 presented a convex model for the uncertainties in the stiffened panel profile. The convex model can predict the weakest panel profile in a family of panels using the least amount of information about the uncertainties in the geometry of the panel. The final step is to link and tune the previously introduced tools in order to develop a new closed loop design scheme which yields better and more realistic optimum panel designs. Matching the different components together is essential in order to obtain a robust and efficient design tool.

Two design schemes will be presented in this chapter. The first is the one introduced in Chapter (1) and shown here in Figure (6.1). In this scheme the designer is required to satisfy a specific design constraint, in this case the minimum failure load of the panel is specified. The design process starts with a random imperfection profile to be used in the nonlinear finite element analysis. The result obtained from FEPAD is a first optimum design that is now fed into the manufacturing simulation. The cure cycle used in this study is the manufacturer's recommended curing cycle given in Chapter (4) and variations in the resin density are the only source of imperfections considered. The output of the manufacturing model is an ellipsoidal set of panel profiles defined by a nominal profile $\vec{q}^{\,o}$ and a deviation vector $\vec{\omega}$. Next the convex model starts by calculating the sensitivity of the failure load with respect to the different imperfection parameters using the nonlinear finite element code FEPA. These sensitivity parameters are then used along with the nominal profile $\vec{q}^{\,o}$ and the semiaxes length vector $\vec{\omega}$ in order to determine the weakest panel profile of the set. The second design iteration starts now, using the weakest panel profile obtained previously, the optimization is restarted and a new optimum design is obtained. The obtained design is now fed into the manufacturing model and a new set of imperfect panel profiles that corresponds to the new design is obtained. Once again the convex model determines the weakest panel profile in the ellipsoidal set and the process is restarted.

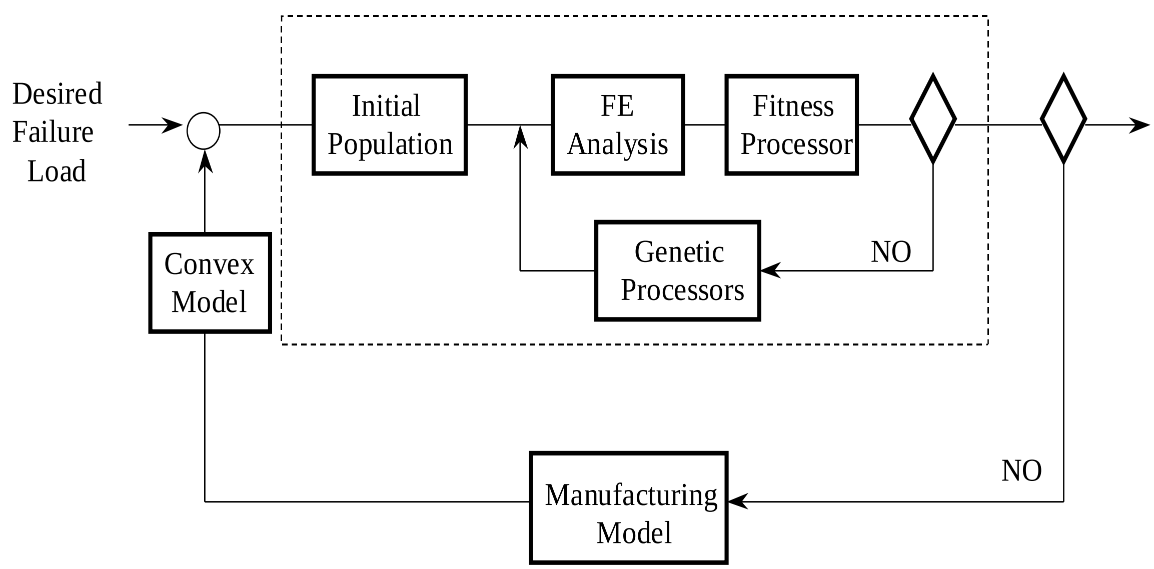

Figure (6.1) : First proposed closed loop design scheme

The objective of this study is to obtain a panel design that can sustain the specified minimum failure load when analyzed using the actual imperfection profile predicted by the manufacturing model. After obtaining the nominal imperfection profile corresponding to every optimum design, the failure load of the panel is recalculated. Convergence of this process is defined using the difference between the required minimum failure load and the actual panel failure load. Results of this design scheme will be presented in Section 6.1 of this chapter.

The second design scheme presented in this chapter is illustrated in Figure (6.2). In this case the manufacturing and the convex models are incorporated inside the nonlinear design optimization tool (FEPAD). This means that for every individual design in any population of panels suggested by the genetic algorithm, a set of possible imperfect profiles is generated and the weakest panel in this set is determined using the convex model. In other words, the weakest panel profile used in the nonlinear analysis is now specific to the design under consideration in the optimization, in contrast with the previous scheme in which one imperfection profile is used throughout the optimization. The incorporation of both the manufacturing and the convex models in the design optimization module led to a sharp increase in the computation time required. However this will be later justified by the significant weight savings achieved by using the new scheme.

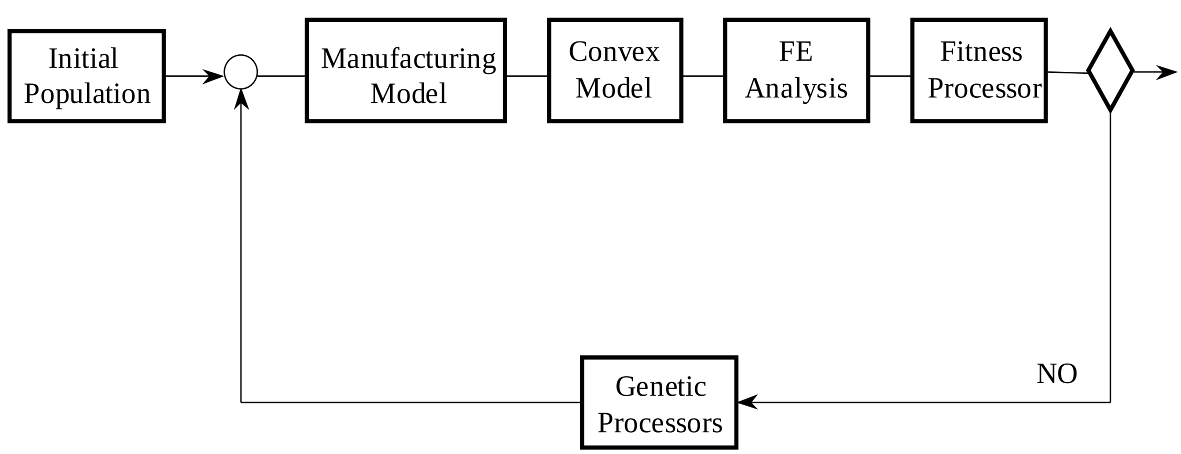

Figure (6.2) : Second suggested design scheme

6.1 Results of the First Design Scheme

In this section, results obtained from the first closed loop scheme are presented. For a detailed description of the problem geometry, loading and boundary conditions, the reader is referred to Chapter (3) of this dissertation. The formulation of the optimization problem was also given in Chapter (3).

In order to start the design process, we need to generate a random imperfection profile that will be used here to initiate the optimizer (and will be disregarded in the following design cycles). In this example, a panel with a $[\pm 45/90/0]_s$ stacking sequence was cured using the manufacturing model, and the resulting nominal imperfection shape (shown in Figure (6.3)) was used as initial imperfection profile.

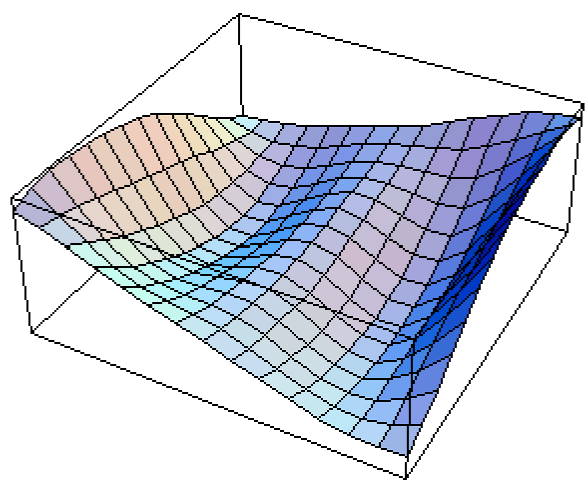

Figure (6.3) : Imperfection profile used to initialize the design process

The first optimization run was then performed and the results are listed in Table (6.1). The optimum design was then fed to the manufacturing model and a corresponding set of imperfection profiles generated. The nominal imperfection profile corresponding to the first optimum design is shown in Figure (6.4). In order to assess the validity of this design, the panel was analyzed with the actual imperfection profile of Figure (6.4). The result was a failure load of *40740 N*, which is far below the specified minimum failure load in this case of *56000 N*. This result resumes the motivation of this study, since it is clear that panels obtained using arbitrary imperfection profiles are very likely to fail at lower load levels than their corresponding design load.

Table (6.1) : **Near Optimum Feasible Designs along with their Expected Failure Load Obtained by the First Design Cycle**

Panel Mass (Kg)	$P_{failure}$ (Newton)	Plies	Laminate S: skin B: Blade
0.523743	59500	(S)-[6]	$[0_3]_s$
		(B)-[26]	$[-45/0_2/90/0/90/0_6/45]_s$
0.615592	70000	(S)-[8]	$[0_4]_s$
		(B)-[26]	$[-45/0_2/90/0/\pm 45/0/90/0_3/45]_s$
0.615592	56000	(S)-[8]	$[90/0/90/0]_s$
		(B)-[26]	$[0_2/90/-45/90/\pm 45/90/0_4/45]_s$
0.688348	66500	(S)-[10]	$[0_4/90]_s$
		(B)-[24]	$[-45/0/45/90/0_2/-45/0_4/45]_s$
0.688348	56000	(S)-[10]	$[0_5]_s$
		(B)-[24]	$[0/\mp 45/-45/90/45/0/-45/0_2/45/90]_s$
0.707441	70000	(S)-[10]	$[0_5]_s$
		(B)-[26]	$[0_2/-45/90_2/\pm 45/90/0_4/45]_s$

The next step is to use the convex model to determine the weakest panel profile corresponding to the first optimum design. This weakest panel profile is now used to start the second design cycle. Results of the second design optimization are shown in Table (6.2). Once again the resulting optimum design is fed into the manufacturing model and a corresponding set of imperfect profiles is generated.

The nominal imperfection profile corresponding to the second optimum design is shown in Figure (6.5).

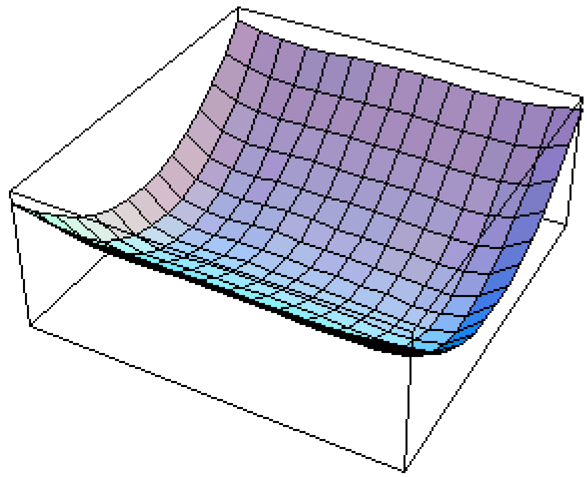

Figure (6.4) : Predicted nominal imperfection profile for the first optimum design

Once again, in order to validate the newly obtained design, nonlinear finite element analysis is performed on the suggested panel with the corresponding predicted nominal imperfection profile.

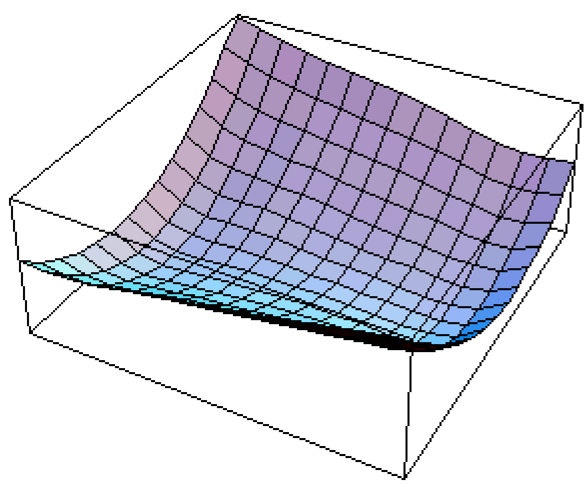

Figure (6.5) : Predicted nominal imperfection profile for the second optimum design

The panel failed at *53200 N* which is still below the specified design load of *56000 N*. However, the difference between the required failure load and the actual failure load is less in the case of the second optimum design than in the first case, which suggests convergence of the process toward a more reliable design.

Table (6.2) : **Near Optimum Feasible Designs along with their Expected Failure Load Obtained by the Second Design Cycle**

Panel Mass (Kg)	$P_{failure}$ (Newton)	Plies	Laminate S: skin B: Blade
0.539223	60000	(S)-[8]	$[0/-45/45/90]_s$
		(B)-[18]	$[-45/45/90/90/0/-45/90/45/90]_s$
0.558316	57000	(S)-[8]	$[0/-45/45/0]_s$
		(B)-[20]	$[\mp 45/90_2/0_2/90_2/\mp 45]_s$
0.669256	60000	(S)-[10]	$[0/-45/90/45/90]_s$
		(B)-[22]	$[0_2/-45/90_2/45/0/-45/0/45/90]_s$
0.707441	60000	(S)-[10]	$[\mp 45/0/\mp 45]_s$
		(B)-[26]	$[0/\mp 45/0/90/\mp 45/0/-45/0_2/45/90]_s$
0.726533	60000	(S)-[10]	$[0/\mp 45/\mp 45]_s$
		(B)-[28]	$[0_2/-45/90_2/0/\pm 45/90/0_3/45/90]_s$

A third design iteration is now performed in order to ensure the convergence of the new scheme. The iteration started by finding the weakest panel profile corresponding to the second optimum design using the convex model. Next the optimization was restarted using the new panel profile. Results of the third optimization run are given in Table (6.3). Finally, the latest optimum design was fed into the manufacturing model and the corresponding set of imperfection profiles was obtained. Nonlinear finite element analysis of the third optimum design combined with its predicted nominal imperfection profile estimated a failure load of *56200 N*, which is slightly higher than the required failure load of *56000 N*. It is natural to conclude that the first suggested design scheme is convergent and that it leads to a more reliable optimum. However, it was also noticed that the weight of the obtained optimum design increased as the process converged. This suggested the second design scheme presented next.

Table (6.3) : **Near Optimum Feasible Designs along with their Expected Failure Load Obtained by the Third Design Cycle**

Panel Mass (Kg)	$P_{failure}$ (Newton)	Plies	Laminate S: Skin B: Blade
0.611980	60000	(S)-[10]	$[0_3/90_2]_s$
		(B)-[16]	$[0/-45/0_2/90/\pm45/45]_s$
0.611980	54000	(S)-[10]	$[0_2/90/0/90]_s$
		(B)-[16]	$[0/45/0/90/0_2/\mp45]_s$
0.631073	60000	(S)-[10]	$[0_4/90]_s$
		(B)-[18]	$[0/90/0/90_2/\mp45_2]_s$
0.650165	60000	(S)-[10]	$[0_4/90]_s$
		(B)-[20]	$[0/90/0_2/90_2/45/90/\mp45]_s$
0.669257	60000	(S)-[10]	$[90/0_3/90]_s$
		(B)-[22]	$[0/-45/0_2/90_5/0/45]_s$

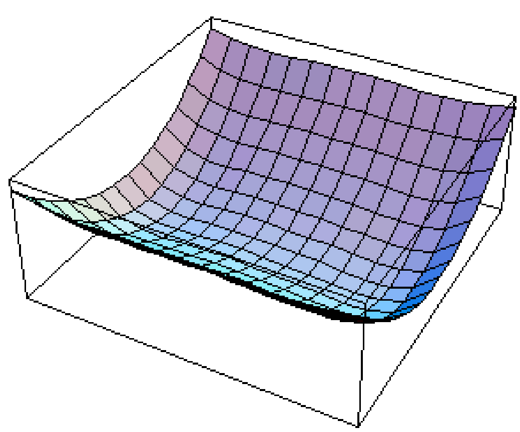

Figure (6.6) : Predicted nominal imperfection profile for the third optimum design

6.2 Results of the Second Design Scheme

In this scheme, the manufacturing and convex models are both incorporated in the nonlinear optimization tool. Thus, for each design in a given population of designs suggested by the genetic algorithm optimizer, the manufacturing model finds the corresponding set of possible imperfect panels and the convex model gets the weakest profile in this set of panels. The nonlinear finite element analysis is then performed using this weakest panel profile. In this approach, every design has its own corresponding weakest panel profile. This in contrast with the first scheme in which only one imperfection profile is used during the nonlinear finite element analysis of all the panels analyzed in the optimization module. This scheme is expected to give a more efficient optimum design at the price of a higher overall computational cost.

This process has been applied to the same problem in Section 6.1, and the results are shown in Table (6.4). When tested, the optimum design fails at *56320 N* when combined with its nominal imperfection profile shown in Figure (6.7). It is clear that a great deal of weight reduction has been achieved by the new scheme when compared to the previous one. That in addition to the elimination of the iterative nature of the process presented in Section 6.1. However the second scheme required approximately three times the computational time needed to perform the three cycles presented in Section 6.1.

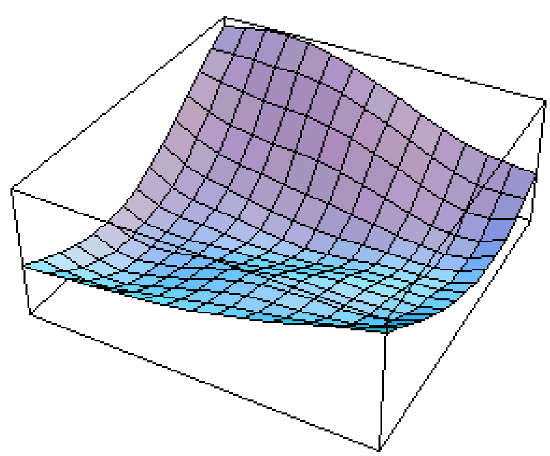

Figure (6.7) : Predicted nominal imperfection profile for the new optimum design

Table (6.4) : **Near Optimum Feasible Designs along with their Expected Failure Load Obtained by the Second Suggested Design Scheme**

Panel Mass (Kg)	$P_{failure}$ (Newton)	Plies	Laminate S: Skin B: Blade
0.497427	57000	(S)-[10]	$[-45/0_3/45]_s$
		(B)-[4]	$[90/0]_s$
0.535611	60000	(S)-[10]	$[0_3/\mp 45]_s$
		(B)-[8]	$[0_2/90/0]_s$
0.535611	57000	(S)-[10]	$[0_2/-45/0/45]_s$
		(B)-[8]	$[0_2/90/0]_s$
0.554704	60000	(S)-[10]	$[0/-45/0_2/45]_s$
		(B)-[10]	$[0_2/90_2/0]_s$
0.554704	60000	(S)-[10]	$[0/-45/0_2/45]_s$
		(B)-[10]	$[0_2/90_2/0]_s$
0.573796	60000	(S)-[10]	$[0_3/90/0]_s$
		(B)-[12]	$[90_2/0/90_2/0]_s$
0.573796	57000	(S)-[10]	$[0/-45/0/90/45]_s$
		(B)-[12]	$[0_2/90/0_3]_s$

Notice that a shear load of 25 % the axial compressive load has been added to the second formulation to ensure the presence of 45 degree plies in the final optimum design. These plies are essential to carry any shear load the panel might be subjected to. It is however clear that all seven near optimum designs are lighter than the best design from the previous scheme. A weight saving of 23 % was achieved by the second scheme over the first. This is at the price of an increased calculation time of up to three times the computation time required by the first scheme.

Finally, a comparison between the newly obtained results and those obtained with a traditional open loop design scheme [1] are presented. The previous design was studied by Perry [1] where a finite strip analysis was used along with a continuous optimization code in order to obtain an optimization design tool for postbuckling behavior. The imperfection profile employed in [1] was an assumed profile of the same shape as the first buckling mode of the panel and with maximum amplitude of 0.1% the length of the panel. By examining Table(6.5) we notice that the panels obtained by NLPANOPT [1] failed at a much lower load than their design load, this in contrast with those panels designed using the suggested close loop design schemes. It is also noticeable that the second design scheme led to the lighter design among all four design processes.

Table(6.5) :Comparison with Existing Optimum Designs

Design Tool	Panel Mass (Kg)	$P_{failure}$ (Newton)	Plies	Laminate S: Skin B: Blade
NLPANOPT	0.583166	31000	(S)-[8] (B)-[16]	$[45/-45/90/0]_s$ $[45/-45/90/0_6]_s$
NLPANOPT with Imperfection	0.583725	31000	(S)-[8] (B)-[16]	$[45/-45/90/0]_s$ $[45/-45/90/0_6]_s$
Scheme 1	0.611980	56200	(S)-[10] (B)-[16]	$[0_3/90_2]_s$ $[0/-45/0_2/90/\pm 45/45]_s$
Scheme 2	0.554704	56320	(S)-[10] (B)-[10]	$[0/-45/0_2/45]_s$ $[0_2/90_2/0]_s$