SAWE Paper No. 3330
Category No. 12

WEIGHT OPTIMIZATION OF FILAMENT-WOUND PRESSURE VESSELS

Dr. Myles L. Baker
M4 Engineering, Inc.

For Presentation at the
63rd Annual Conference
of
Society of Allied Weight Engineers, Inc.
Newport Beach, California, 17-19 May, 2004

Abstract

A software suite tailored to the analysis and optimization of filament wound composite pressure vessels has been developed. The software has been applied with success to simple pressure vessels, as well as to solid rocket motor cases. The optimization process employed is a mixed low-fidelity/high-fidelity approach, in which the basic pressure vessel geometry and winding angles are determined using a low fidelity model based on laminate theory. These results are then used as a starting point for a high fidelity optimization where the details of the winding schedule are tailored to provide the lightest possible bottle. The high fidelity component of the optimization is performed using a detailed winding simulation (COBSTRAN) and a composite progressive failure analysis (GENOA). The software is very easy to use, and provides a useful tool for pressure vessel design.

Introduction

In many ways, composite materials are ideally suited to pressure vessel applications. Two main factors contribute to this suitability: The loads in a cylindrical pressure vessel are inherently anisotropic (hoop loads are approximately double the axial loads), and the loads are dominated by tension (in the fibers, if the design is done correctly). When the excellent performance of composite materials in tension is considered, it is clear that composites are an ideal choice for pressure vessel applications.

The manufacturing method of choice for composite pressure vessels is filament winding, in which the composite fibers are passed through a resin bath, and the "wet" fibers are then wound around the pressure vessel (defined as a mandrel on a rotating axis) until the desired amount of material is applied. Examples of different filament-winding patterns are shown in Figure 1. The part is then cured in an autoclave, and the mandrel removed. There are variations of this process. In many applications (especially where permeability is in important issue), the mandrel is replaced with a metal or plastic liner that is not removed, but becomes an integral part of the tank. In other applications, unidirectional prepreg composite tape is used instead of wet fibers in the winding process.

In any of these variations, defining the winding pattern requires some thought. First, it must be ensured that the domes of the pressure vessel have sufficient strength, and second, care must be taken to ensure that the fibers are uniformly distributed around the circumference, and that no “bald spots” exist in the winding pattern. The most common solution to the dome problem is to use geodesic domes, in which (1) the fibers follow a friction-free path across the dome, and (2) the curvature of the dome is tailored to keep constant stress in the fibers. This fully defines the domes in terms of the cylinder properties, making it possible to reduce the optimization problem to the problem of defining an optimal winding on the cylindrical portion of the pressure vessel alone.

This paper documents a process for optimizing the winding schedule for a general composite pressure vessel. It first performs a preliminary optimization of the composite material requirements based on a low-fidelity analysis, using netting theory and geodesic winding assumptions. The results of the low-fidelity optimization are then used to initialize a high-fidelity optimization, in which the path of each individual fiber tow is traced around the tank, and a detailed progressive failure finite element analysis is performed.

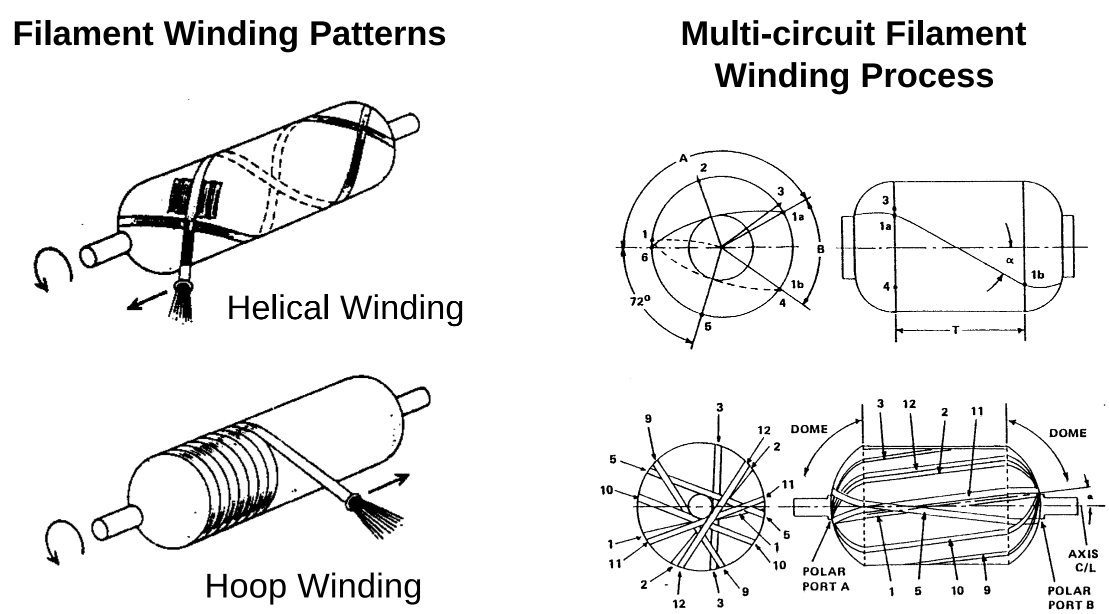


Figure 1: Typical filament winding patterns.

The Motor Case Design Software

In a joint venture with the Alpha Star Corporation, M4 Engineering has recently developed a software package for optimizing the design of composite pressure vessels. The initial focus has been on solid rocket motor cases (hence the name of the software: Motor Case Design), but the software is equally applicable to pressure vessel applications. The analysis and design process implemented in the Motor Case Design software includes a low-fidelity step, in which simplified analyses are performed to determine the optimal geometry, winding angles, and approximate ply thicknesses. In this optimization, the winding angles are limited to those angles that result in closed star patterns and uniform coverage. This involves a multi-level optimization process, in which the possible "good" winding patterns (those that result in uniform coverage) are surveyed, and each potential pattern is optimized for minimum weight subject to strength constraints. This results in a set of minimum weight designs for different winding patterns. The lowest weight of these designs is selected as the optimum.

Once the low-fidelity optimization step is complete, a high-fidelity analysis and optimization is performed, in which a detailed simulation of the winding process is performed. In this simulation, the path of each individual tape circuit is simulated, and a structural analysis is performed, including the effects of tape tension. A structural progressive failure analysis is then performed to determine the actual failure loads and mechanisms. Based on the results of the high-fidelity analysis, the ply schedule is tailored to ensure that the design meets the required strength criteria. In this high-fidelity optimization phase, the case geometry and winding angles are held constant, and only the number of plies (hoop and helical) are varied to obtain the lightest possible design with the required strength

One important feature of the Motor Case Design software is the ability to perform a variable-fidelity analysis and optimization. This allows a very rapid assessment of the overall performance of a pressure vessel using a low-fidelity approach, as well as a detailed assessment of the design's performance, including nonlinear progressive failure analysis, in a high-fidelity option. These approaches have been unified into a nearly seamless process.

Winding Model

The low-fidelity process in the MotorCaseDesign (MCD) software has a relatively simple winding model based on the no-slip assumption. In this winding model, it is assumed that (1) the tension in the fibers is constant during the winding process, and (2) there is no friction between the fibers and the part. These assumptions lead to the "geodesic" winding pattern, which provides a simple specification of the winding path based purely on equilibrium considerations (if the fiber was placed in any other position, the lack of friction would make it "slip" into the geodesic winding pattern).

The main features of the geodesic winding pattern are shown in Figure 2. The most important is the winding angle, which is simply a function of the current radius (distance from the tank axis to the winding surface) and the pole radius (the radius of the hole in the windings at the ends of the tank).

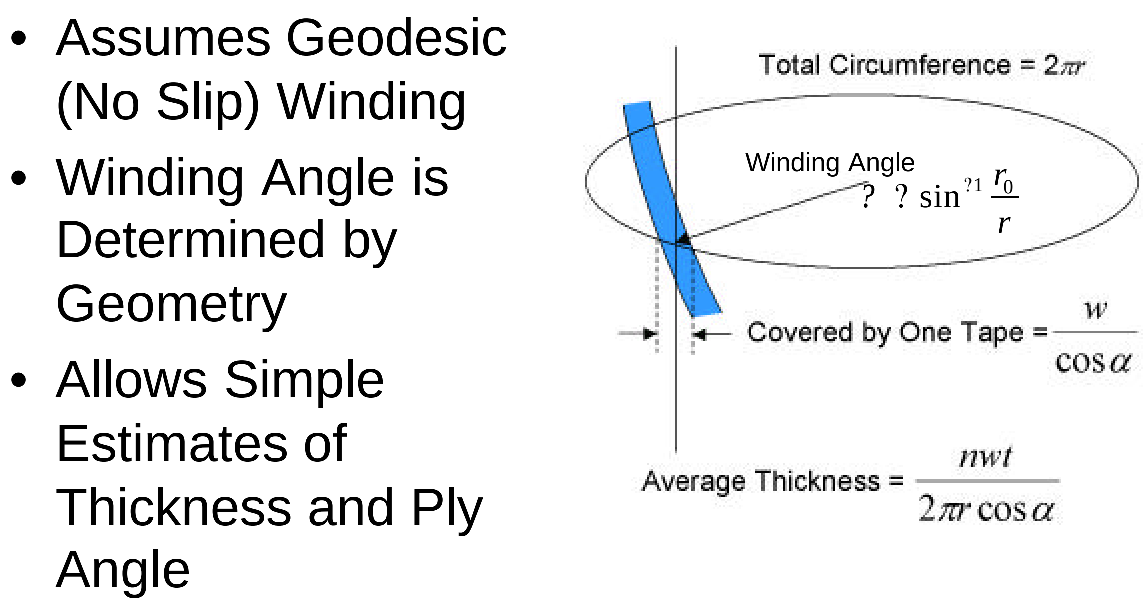


Figure 2: Geodesic winding patterns.

Low Fidelity Analysis and Optimization

The low-fidelity software described above has been implemented along with a simple graphical user interface into a stand-alone software program suitable for performing simplified design of composite rocket motor cases. All functionality of the low-fidelity software is not available from the user interface, but enough is available to provide a useful tool for "quick-look" sizing efforts.

High Fidelity Analysis and Optimization

While the optimization process described above is a very useful tool to determine the approximate optimum design, many effects are neglected in the low-fidelity optimization. These include the effects of the detailed path the composite fibers take during the winding process, the effects of tape tension and prestress, and the detailed failure mechanisms that are important for composite structures. In order to address these issues and to ensure that the optimal design developed by the Motor Case Design software is manufacturable and that it is really capable of withstanding the required loads, a second, higher-fidelity optimization step can be performed.

In the high-fidelity optimization, the goal is to identify the minimum integer number of hoop and helical plies required to withstand the required loads. Since a failure in the dome of a composite rocket motor case is much more dangerous than a hoop failure (in the cylinder), an additional margin is built into the process to ensure that the failure mechanism will involve a hoop failure rather than a dome failure. In order to accomplish this, the integer optimum is defined as the design that can withstand the required loads, but which will fail if hoop or helical plies are removed.

The optimization process is initialized with the results from the low-fidelity optimization, which gives a good initial guess of the total number of hoop and helical plies required. If this initial design fails under the specified loads, the number of hoop and helical plies is increased until the design can withstand the applied loads. Then the design is modified, with individual hoop and helical plies removed. The number of plies is adjusted until the design is found that can barely withstand the applied loads.

This process is implemented through an automated scripting of the COBSTRAN and GENOA codes, and has been applied with excellent results. The high fidelity process is not available in all versions of the Motor Case Design software, as both COBSTRAN and GENOA are required.

Optimizing for a Specified Failure Location

One interesting aspect of pressure vessel design is the impact that failure location has on the safety of the overall design. While any failure of a high-pressure tank is potentially catastrophic, a dome failure (failure at the end) is potentially much more dangerous than a hoop failure (failure in the middle). This is primarily due to the fact that a dome failure has the potential to turn the tank into a missile as the high-pressure gas escapes from the breach.

In order to address this issue, the MCD software has the capability to develop tailored designs that fail primarily in the hoop region. This provides increased overall safety at a slight weight penalty.

Designing a Motor Case

In order to design a new motor case, simply select the "Design New Motor Case" option from the main application's File menu. This will invoke a wizard that leads the user through the process of setting up and executing the optimization problem. The first step is to define the motor geometry, which is performed using the wizard screen shown in Figure 2. The Case Length is the distance from tangent line to tangent line, and the Case Radius is the radius of the cylindrical section of the case.

The Minimum Pole Radius and Maximum Pole Radius represent the smallest and largest permissible pole openings. A single pole radius cannot be specified because a geodesic winding is assumed, which leads to a coupling between the winding angle and the pole radius. The minimum and maximum pole radius must be specified so that there is at least one permissible winding with a pole radius in that interval. Recall that the units of length are arbitrary, and simply must be consistent with the units in the materials.dat file.

Once the geometry is specified, the next page of the wizard (Figure 3) allows the user to enter the design stiffness requirements and load conditions the motor case. The software supports minimum stiffness specifications for both bending and torsional stiffness, in consistent units (inch- lb/radian, Newton-meter/radian, etc...). If there is no minimum stiffness requirement, simply leave the default value of zero.

The software supports internal pressurization as well as tension (compression), torsion, and bending loads. These are entered in a spreadsheet format, along with a load case dependent safety factor. It is assumed that tension, torsion, and bending loads are applied uniformly to the cylindrical section of the motor case, and that the domes are subject only to pressurization loads. The software allows any number of load cases to be defined, and additional rows are automatically added to the table as new load cases are added.

Finally, the materials must be selected, using the wizard page shown in Figure 4. This includes selecting the material to be used for hoop windings, selecting those to be used for helical windings, and selecting a nominal tape width. The final tape width will be slightly different from the nominal tape width to ensure uniform coverage of the helical plies.

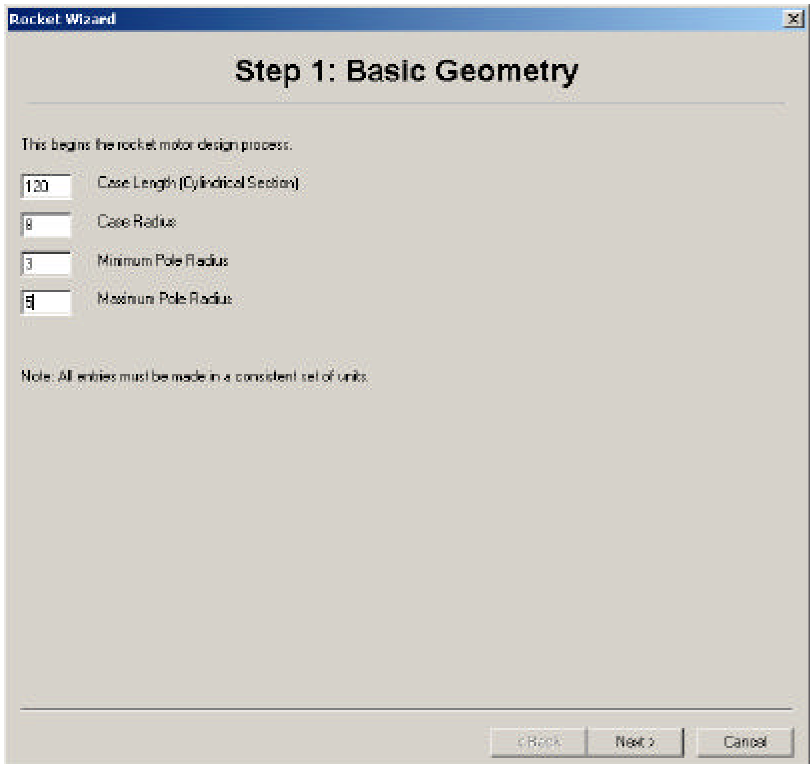


Figure 3: Basic Geometry Input for Motor Case Design.

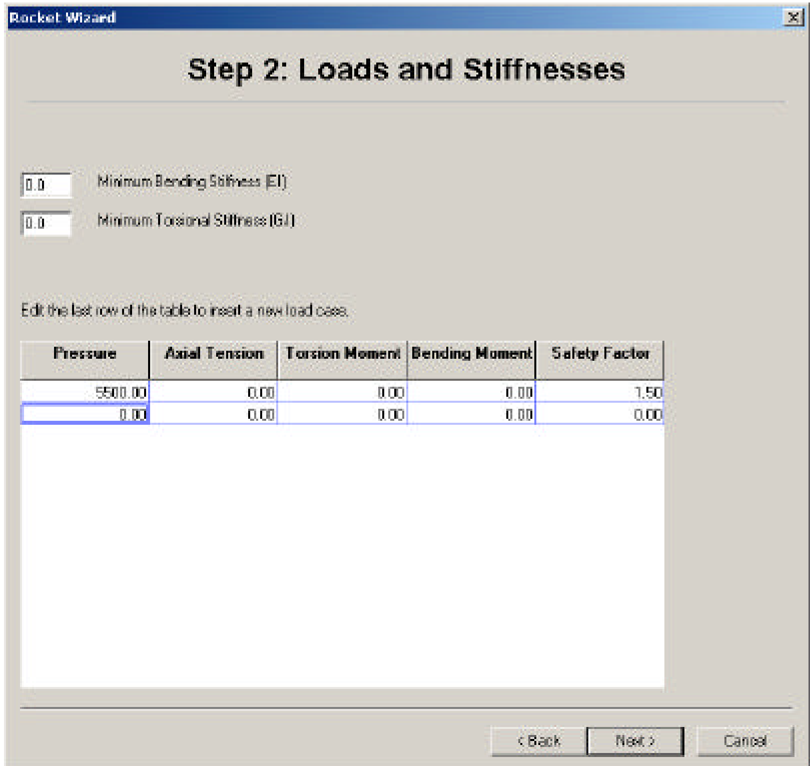


Figure 4: Load Case Input for Motor Case Design.

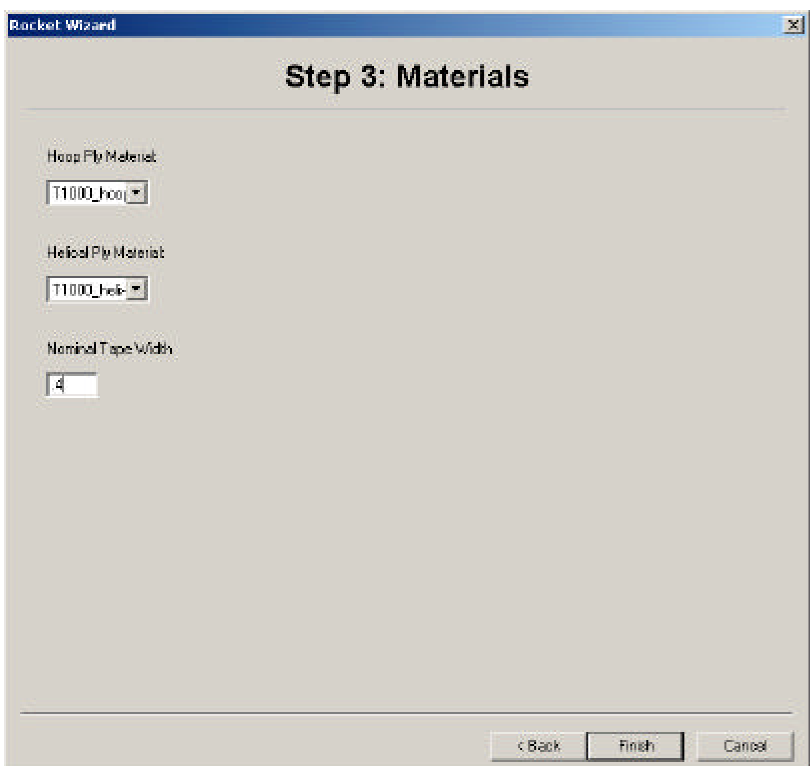


Figure 5: Material Selection for Motor Case Design.

Low Fidelity Optimization

Once the geometry, loads, and materials are defined, the optimization of the motor case begins. This process contains two main parts. First, the software loops over the possible winding patterns that lead to uniform-coverage "star" patterns. For each winding pattern, the software determines the combination of helical winding angle, tape width, and pole size that gives a uniform coverage winding. Those winding patterns that have pole opening sizes in the allowable range are then identified, and the amount of composite material (total thickness of helical and hoop plies) required to withstand the applied loads is determined. The lightest of these designs is then selected as the optimum. This is presented to the user as an optimization log, which shows the winding patterns considered, and the optimization results for those that have acceptable pole diameters. A final summary for the overall optimum result is then provided. The log supports normal windows cut-and-paste functionality, so the results can be captured for reporting and documentation purposes. A typical optimization log is shown in Figure 5.

Once the optimum design has been identified, a geometric model of the resulting motor case is constructed and displayed in a 3-D viewing window (Figure 6). The inner and outer surfaces of the composite pressure vessel structure are shown, which allows the relative thickness distribution to be easily seen and verified.

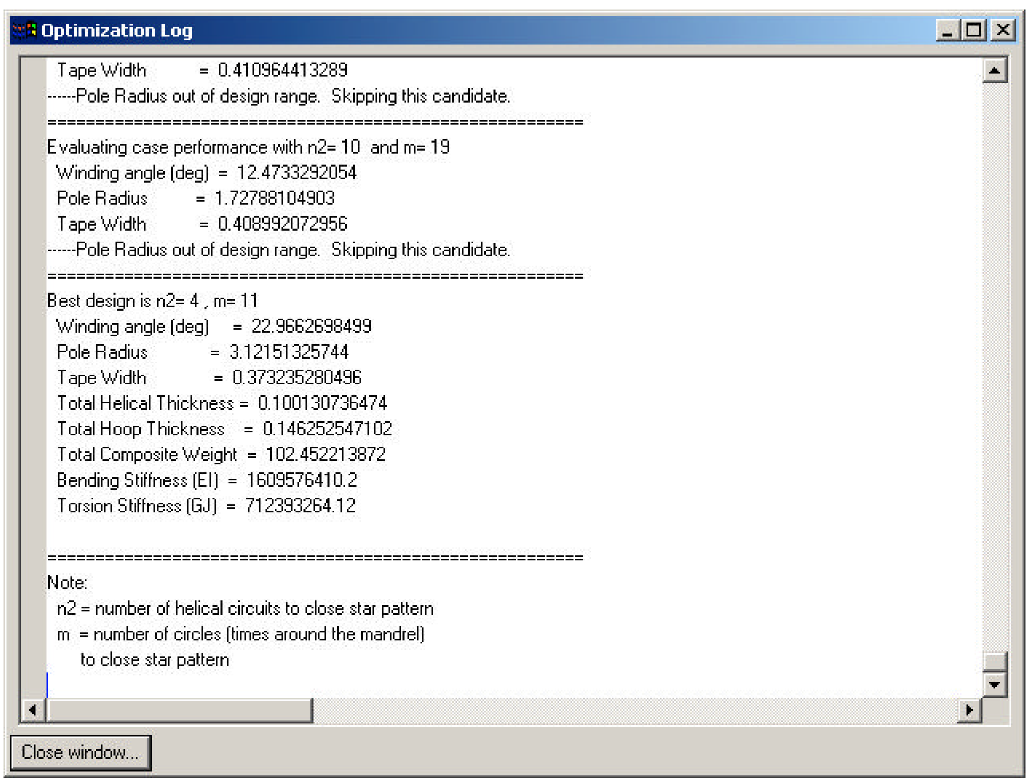


Figure 6: Low-fidelity Optimization Log Output.

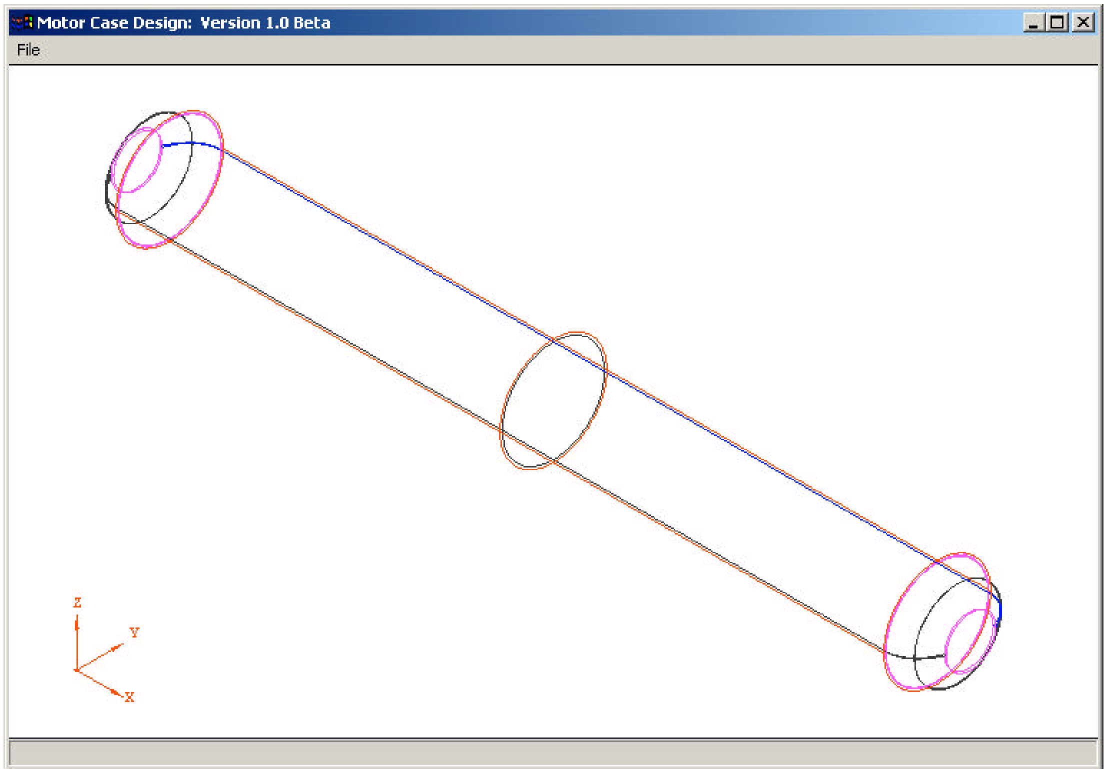


Figure 7: Geometric View of Optimized Motor Case.

High Fidelity Optimization

The MotorCaseDesign software has been designed to work with COBSTRAN and GENOA to perform detailed high fidelity manufacturing simulation and progressive failure analysis inside an optimization loop. In this process, the low-fidelity optimization results are used as a starting point, and high-fidelity models are built based on this configuration. A detailed progressive failure analysis is then performed and the failure condition compared to the design condition. The optimization process then automatically updates the winding schedule (keeping geometry constant) to determine the minimum number of hoop and helical plies necessary to withstand the applied loads. This results in an optimum design, where the basic geometry and winding angles are selected based on a relatively low-fidelity process using laminate theory, and the details of the winding schedule are generated using detailed winding simulation and progressive failure analysis.

Exporting Geometry

Geometry can be exported to external modeling software through the IGES format. This is initiated by selecting File/Export IGES from the main window menu. While the current software only supports the IGES format, support for other file formats (STEP, BREP, STL) can easily be provided if necessary.

Applications

The MotorCaseDesign software has been applied to numerous example problems. One of the most instructive is the design of a solid rocket motor case based on an existing configuration. The design length of the case (the cylindrical portion) is 120 inches, and the design radius is 8 inches. The pole radii are constrained to be between 2 and 4 inches. The low-fidelity optimization was performed first, in which numerous winding schedules (particularly for the helical windings) were investigated, and the resulting pole radii calculated. This is shown in tabular form in Figure 8. While a detailed discussion is beyond the scope of this paper, the integer parameters defining the rows and columns of the table define the "star" pattern of the helical windings, and how many circuits are required before the pattern repeats itself.

Figure 8 shows the pole radii calculated for each candidate winding. Since the pole radius was constrained to be between 2 inches and 4 inches, many of the windings are infeasible. Those that satisfy the pole radius requirement are highlighted in yellow, and are selected for further analysis and ply thickness optimization based on laminate theory. The results of these analyses are shown in Figure 9. The optimal winding schedule results in a total composite weight of ~102 pounds, and a pole radius of ~2.77 inches.

Now that the winding pattern is set, a high fidelity analysis/optimization is performed in COBSTRAN/GENOA. The results of the final analysis are shown in Figure 10. The initial damage initiation occurs at approximately 7,600 psi of internal pressure, with final failure at around 7,640 psi.

Example of Winding Optimization

- Varied winding parameters (integers)
- Optimized thickness for each winding possibility
- Table Shows Pole Diameters
- Yellow are "Feasible" Windings

M-N2

N2	1	2	3	4	5	6	7	8	9	10
1	0.11668	1.979833	3.535243	4.694493	5.516207	6.093535	6.503852	6.801238	7.021498	7.188122
2	0.097354	1.053517	1.962396	2.790899	3.52167	4.151015	4.684725	5.133441	5.509348	5.824264
3	0.094671	0.735317	1.361166	1.96002	2.522851	3.043769	3.519861	3.950666	4.337642	4.683451
4	0.091316	0.572629	1.047678	1.51065	1.956989	2.383014	2.786084	3.164506	3.517499	3.84497
5	0.085757	0.47108	0.853342	1.229209	1.596135	1.951918	2.294687	2.623064	2.936019	3.232923
6	0.08796	0.409151	0.728695	1.044415	1.354768	1.658355	1.953956	2.240509	2.517197	2.783369
7	0.085239	0.360565	0.635013	0.906998	1.175522	1.439656	1.698552	1.951473	2.197738	2.436841
8	0.086282	0.327185	0.567636	0.806396	1.042783	1.276153	1.505906	1.731496	1.95244	2.168285
9	0.091396	0.305517	0.519434	0.732124	0.943105	1.151913	1.35811	1.56129	1.76108	1.957116
10	0.081891	0.274558	0.467235	0.659017	0.849547	1.038481	1.225491	1.410266	1.592518	1.771979

Figure 8: Winding Matrix Investigated in Low Fidelity Optimization.

Winding Optimization (cont'd)

- Case Weight (lb)

M-N2

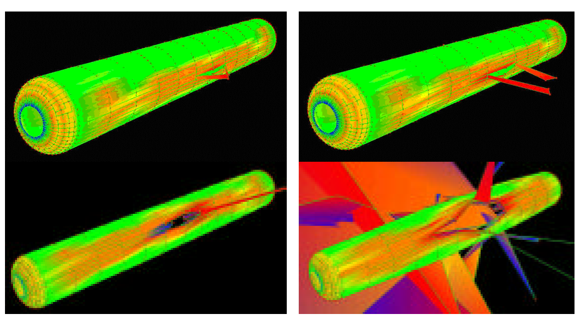
N2

	1	2	3	4	5	6	7	8	9	10
1			102.6807							
2				103.3616	102.6723					
3					103.9925	102.6749	102.9704	104.2667		
4						103.3739	102.4736	102.6698	102.8901	104.4194
5							104.4192	103.7705	102.9768	102.5087
6								104.501	104.0045	103.3809
7									104.5593	104.1675
8										104.596
9										
10										

Optimum

Figure 9: Optimized composite weight for each feasible winding.

HiFi Analysis Results



Damage Progression to Final Failure

Figure 10: Results of High Fidelity Progressive Failure Analysis.

Conclusion

The MotorCaseDesign software has been shown to be an easy-to-use and useful tool in the design of composite pressure vessels, including those with externally applied bending/torsion loads (such as rocket motor cases). The coupled low-fidelity/high-fidelity optimization is a unique capability that allows the definition of the geometry and the basic winding schedule early on, with the details of the number of circuits of each type of winding determined by higher fidelity analysis. It is expected that this software will find wide application in the pressure vessel industry.

Author's Biography

Dr. Myles Baker is the founder of M4 Engineering, Inc. He is an expert in structural analysis and optimization as well as in multidisciplinary process integration and optimization. He has worked for Jacobs Engineering (Naval Systems Group), Boeing (Phantom Works), and McDonnell Douglas (Douglas Aircraft). He received his Ph.D. from UCLA in 1996.

References

1. *Filament Winding Composite Structure Fabrication (2nd Edition)*, S.T. Peters, W.D. Humphrey and R.F. Foral, SAMPE Publishing, 1999, ISBN 0-938-994-81-6.
2. *GENOA User's Manual*, Alpha Star Corporation, Long Beach, CA, 2004.