REDUCING DESIGN COSTS BY INTEGRATING FINITE ELEMENT AND OPTIMIZATION TECHNIQUES

By

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Optimization techniques available for use with the general purpose finite element program ANSYS® are described and applied to several design problems. Combining these technologies in appropriate design situations can lead to improved efficiency in the overall design process. The implications and consequences of using this technology are discussed from a designer's point of view. Details of the method and its implementation are presented through examples of interest to the practicing design engineer.

Mr. Imgrund and Mr. Wheeler have been instrumental in testing and verifying the new design optimization capabilities in ANSYS. ANSYS is a general purpose finite element program developed by Swanson Analysis Systems, Inc. ANSYS has been recognized as a worldwide leader in finite element technology for over 15 years.

INTRODUCTION

In today's competitive marketplace, every manufacturer would like a higher quality, lower cost product. A major obstacle to obtaining this superior design has been the design costs. Many companies are reluctant to commit to redesign projects because of the possibility that no real savings will be found. Designers need tools that will increase the probability that they will find a better design.

The traditional design process uses accumulated knowledge as the basis of new designs. Designs are proposed and prototypes are made and thoroughly tested before a product is determined to be ready for production. This approach suffers from long lead times in bringing a product to market and high design costs.

With the introduction of the finite element analysis technique, this process has been changed. Now the design can be analyzed before prototype testing to eliminate defective designs. This design-analysis loop is able to reduce the long lead time to get a product to market with lower design costs. The weakness of this approach is that it still relies on the accumulated knowledge of the designer to propose a good design.

The ANSYS finite element program has recently implemented the ability to link its finite element analysis capabilities with classical optimization theory to provide true design optimization capabilities. Now the computer can perform design "experimentation" to gain knowledge about a better design.

The potential advantages to using this technology include:

1) Faster response to design change requirements and "What if?" senarios.

2) Reduced costs and time for design and analysis.

3) Reduction or elimination of prototype costs.

4) Lower cost of final design.

5) Increased confidence in final design.

This new technology has some interesting aspects. With the computer accumulating "knowledge" about the design very rapidly, a new understanding of the design on the part of the engineer becomes important. With the present method, comprehending the limits of the possible design range becomes very important. Restricting possible designs without good engineering reason could exclude better designs. Another interesting aspect is deciding who can use this tool effectively. Many organizations have one or two key design personnel who make most major design decisions. Now it is possible for other less involved engineers to contribute significantly and efficiently to major design projects.

FUNDAMENTALS OF OPTIMIZATION

The typical optimization process seeks to minimize or maximize a set of values by changing some attributes of the design, while maintaining other attributes within specified limits. An example of this would be to minimize the weight of a member by varying the thickness along the length subject to a maximum stress limit. The approach used in ANSYS to solve the optimization problem is to minimize a single function by modifying specified design parameters subject to some inequality constraints.

The function to be minimized is defined as the OBJECTIVE FUNCTION. Some typical objective functions are weight and cost. The items which are varied during the process are defined as DESIGN VARIABLES. Some typical design variables are thickness, area, and fillet radius. A design variable is specified by its initial value and the range that the final value must fall within. Those variables which constrain the feasible design space are defined as STATE VARIABLES. Some typical state variables might be maximum deflection, maximum stress, or minimum heat flow. These inequality constraints are specified by their minimum and maximum limits.

The optimization process involves evaluating different finite element models to see which proposed design yields the smallest objective function value in the feasible range. As data is gathered, relationships begin to develop between the objective function, design variables, and state variables, so that future design evaluations are based on the accumulated knowledge.

The constructs available from within the finite element program to support these tasks are the key ingredients for any "easy to use" optimization tool. The ANSYS program has developed an input language that allows:

1) Changing an input parameter from within the program.

2) Calculating an input parameter based on other input parameters.

3) Using the optimization module of the program to control the execution of the finite element solution module.

4) Passing parameters back and forth between the optimization module and solution module.

The finite element model can now be defined in terms of parameters, instead of fixed dimensions. After the solution, the results interpretation module is used to extract the state variable and objective function values and pass them to the optimization module. The optimization module evaluates these results and determines a new set of design variables and the process repeats.

The technique used to determine the new set of design variables is taken from experimental statistics. The global problem is reduced to a set of relationships between the objective function, design variables, and state variables. This reduced problem is then minimized with respect to the objective function and a new set of design variables determined. The minimization is done by fitting a curve through the objective function data points and using a series of one dimensional searches to find the minimum. State variable constraints are included by an extended interior penalty function. This technique is relatively efficient for a small number of design variables (10 or less), is not limited to any particular class of problem that can be solved, does not require derivative information, and is very easy to use.

APPLICATIONS

This technology can be applied any time there is the potential to save money in production costs. One obvious candidate is any high volume production item. Here, any small decrease in cost accumulates quickly due to the volume. As long as the savings exceed the cost of the production change, a real savings can be realized. Another potential candidate is any high cost project where a small change in the design can generate a large savings. Imagine the cost reduction if the insulation on the Alaskan pipeline was one half inch less!

COSTS VS. BENEFITS

Before making the decision to use the method that has been described, the design engineer must also be aware of the potential costs and benefits for his design environment. The benefits expected are lower product cost (as would be true for any optimization effort) and a more efficient and responsive design effort. The costs that can be expected potentially include hardware, software, and training costs.

The lower product cost benefit may come from some combination of the following elements; reduced material cost, lowered prototyping needs, and reduced engineering design/analysis time. Reduced material costs are straightforward. Two examples that will be presented below show material-related cost reductions of $100,000 for a large "one-time" structure and $600,000/year for a small mass produced component. Reduced prototyping costs are realized if the mathematical modelling done on the computer can replace a portion of the prototype development and testing that would have been necessary in its absence.

Reduced engineering design and analysis costs are not as straightforward as the two preceding benefits. If finite element analysis is already being done, the additional engineering manhours should be small, perhaps 10% to 15% higher overall. If hand calculations or other design methods are employed, the manhours expended may be more or less, depending on the nature of the analysis that must be performed. In either case, if even one redesign or reanalysis is necessary, the present method has a clear advantage in the ease of changing design parameters and re-solving the problem. Since time is a constraint in virtually every design task any engineer has undertaken, the design effort all too often ends when a feasible design meeting the specifications is achieved, if it is not too grossly overdesigned. The speed and ease of re-analysis with the present method changes the economics of making the extra effort to improve a design. The added cost and time of redesign and reanalysis is no longer close to the order of magnitude of the original design; it can now be accomplished in a very small fraction of the time and cost.

The costs associated with implementing these optimization techniques with finite element analysis can be broken down into hardware and computer expenses, software royalties, and training costs. If an organization is currently using finite element analysis and/or has the computer hardware in place, the first two items may be costs already being borne. If so, the added expenses of this nature would be incurred from the increased computer time necessary for the multiple analyses associated with optimization. If hardware and software are not available, the present method can be accomplished at the entry level with an investment in hardware below $5,000 and software costs of approximately $300/month. This level of involvement would be suitable for analyses requiring no more computing power than that available with the desktop PC's and linear static finite element analysis. Larger scale applications and more complicated analyses (beyond linear static) can be handled for proportionally higher costs, on hardware ranging from minicomputers to supercomputers. For those who wish no hardware investment, data centers provide an alternative, but perhaps an expensive one due to the repetitive nature of optimization runs.

Effective use of finite element analysis coupled with optimization techniques requires an initial investment in training of the engineering personnel who will be performing the task. The time investment required to achieve adequate knowledge on the part of an engineering staff will vary considerably with their existing expertise in finite element analysis and fundamental knowledge of optimization methods. An educated guess as to the training requirements for a staff who are sufficiently knowledgeable in the use of finite elements might be eight class hours of instruction coupled with hands-on access. Proficiency would be likely to develop after two or three analyses had been completed.

"CHANGING THE NATURE OF THE GAME"

The implementation of optimization coupled with finite element

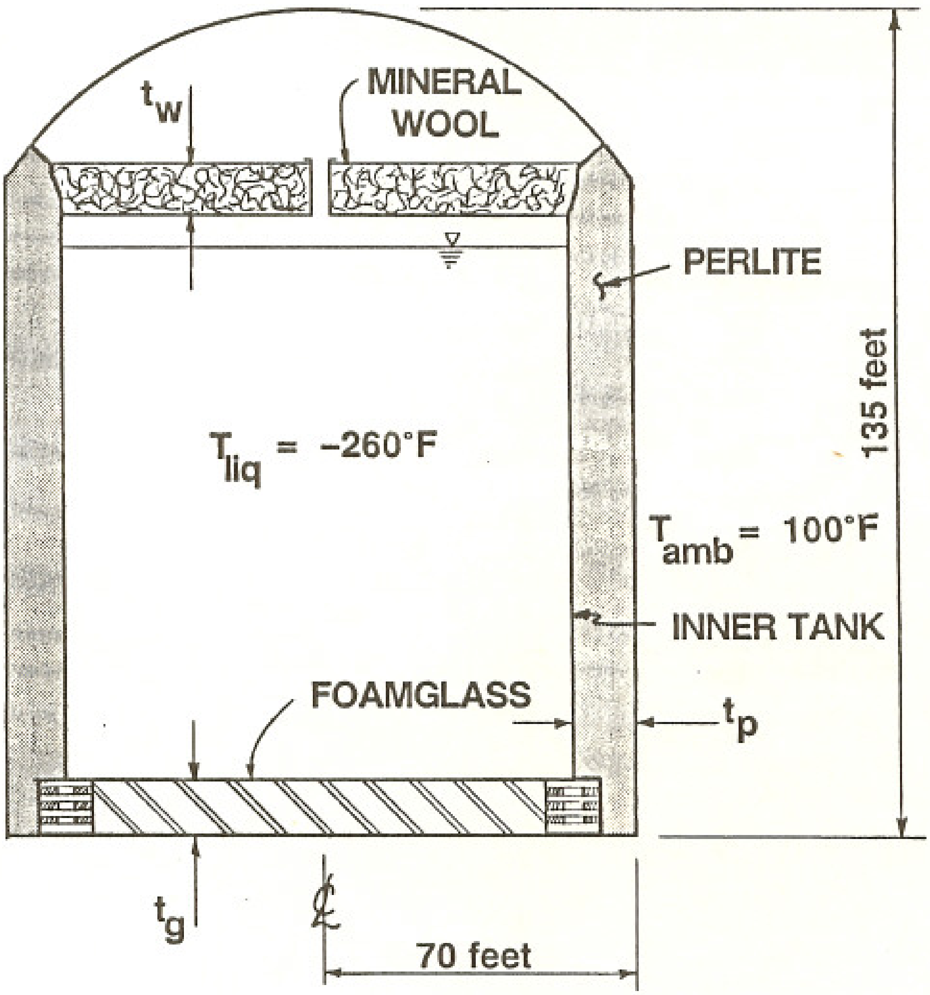

FIGURE 1: EXAMPLE 1 – SECTIONAL VIEW OF LNG TANK SHOWING DESIGN VARIABLES

analysis certainly requires a change in the thought processes of the designers and/or analysts involved. Depending on the structure of the organization adopting these tools, it could also mean changing the nature of individuals' job functions. If design activities and analysis are separate tasks in an organization, they will need to become more closely linked for the techniques described in this paper to be effective. If analysis and design remain distinct, at the very least close communication between the two groups is a must. Designers must think in terms of design variables when working on a new design, and analysts must begin to deal with variables instead of absolutes. For the designer, this change is no more than a formalization of the design process always gone through. The expression of the design concept in terms of variables input to the analysis requires identifying a handful of variables from all the design attributes that characterize the design. Some attributes, such as manufacturing considerations, material to be used, surface finish, corrosion protection, and others must be considered by the designer as well, but these generally fall outside the quantification process of optimizing a design.

IMPLEMENTATION AND EXAMPLES

Two examples solved using this method are presented below to illustrate how it might be used in practice. Both examples represent solutions to design problems that have been encountered and solved in industry.

OPTIMIZATION OF THE INSULATION SYSTEM FOR A LIQUIFIED NATURAL GAS STORAGE TANK

The first example illustrates the potential benefits of these optimization techniques applied to one aspect of a large scale design. The task is to design the insulation system for a low pressure liquified natural gas (LNG) storage tank with a capacity of approximately 300,000 bbl. The tank consists of an inner liquid container and an outer tank serving as the pressure containment (see Figure 1) and insulation jacket. It is presumed for the purposes of this exercise that the inner tank has been sized as required to meet design specifications and will not be changed. LNG is stored at a temperature of -260°F. The insulation system must be designed to allow a maximum heat gain of 150,000 BTU/hr for a full tank with 100°F ambient air and 50°F base temperature (maintained by heaters to prevent ground frost heave). Heat gain in excess of this rate will exceed re-liquification capacity and cause pressure buildup in the tank.

The starting design variable values are those of an existing LNG tank that was built several years ago (to the nearest inch). The primary insulating materials used are mineral wool, perlite, and load-bearing expanded glass foam for the roof, annular space, and base support respectively. The thicknesses of these materials are chosen as the three design variables for the optimization run (t_w, t_p, and t_g in Figure 1). The objective function is chosen to be the sum of those costs influenced by the three chosen design variables; this includes insulation material, installation costs and the erected cost of the steel jacket (outer tank) to enclose the insulation. The cost is input parametrically as:

$$\text{Cost} = C_pV_p + C_wV_w + C_gV_g + C_wV_w + C_sV_s$$

The factors used to calculate the cost (C_p, C_w, C_g, C_w, C_s), are believed to be reasonable since the values chosen reflect approximate unit costs actually incurred during construction increased by an assumed uniform inflation rate. The partial volumes (V_p, V_w, V_g, V_w, V_s) are obtained by appropriate selecting by material and summing in the results interpretation module of ANSYS. The subscripts indicate perlite, wood, foam glass, mineral wool, and steel, respectively.

The finite element model uses 2-D isoparametric thermal solid finite elements, and incorporates seven different insulating materials. The mesh is created using automatic mesh generation capabilities. Boundary conditions are imposed using the design variables defining the geometry.

The design sheets for the original heat gain calculation included six pages dated over a period of two days for one heat gain determination. A fair guess of the manhours required to perform and check these calculations would be four to six hours not including any time required for preliminary rough calculations. The present finite element model and optimization input required five manhours to obtain an adequate finite element analysis/optimization model using the same conservative assumptions as were used in the hand calculations. Reanalysis or redesign would require only minutes of the engineer's time.

The cost function for the original design has a value of \$1,750,000. After twelve optimization loops, the solution converged to a design having a cost function value of \$1,650,000, a cost saving of \$100,000. The solution required 70 CP seconds and 16.5 minutes wall clock time on the Prime 9950. The authors believe that the cost reduction above represents a realistic (order-of-magnitude) attainable savings for this example.

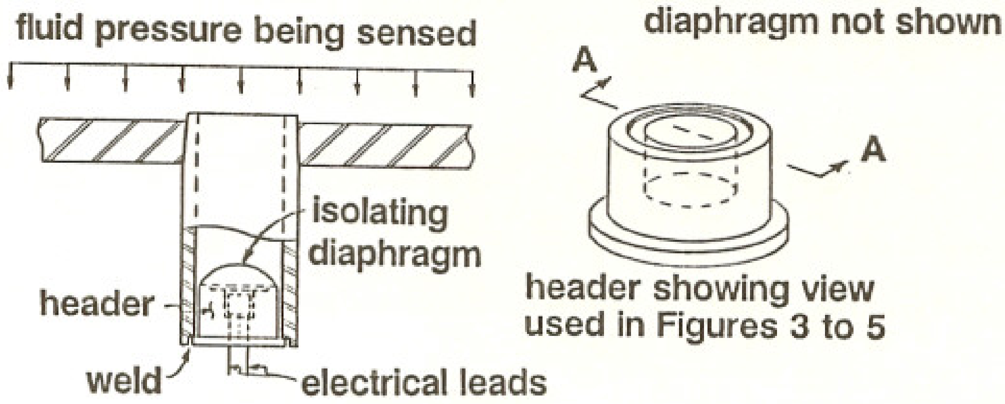

FIGURE 2: PRESSURE TRANSDUCER HEADER EXAMPLE, PARTIAL ASSEMBLY

DESIGN OF A PRESSURE TRANSDUCER HEADER

The second example is an endeavor to decrease the cost of a mass-produced component. The item of interest is the header portion of a pressure transducer assembly, shown conceptually in Figure 2. This design optimization project was undertaken jointly by the authors and the design engineer from the company responsible for the design. Because patents have been applied for, and proprietary materials and welding processes are involved, many numerical details cannot be presented here. Sufficient information is provided to demonstrate how the present method was employed in improving the design.

Company "ABC" produces approximately 200,000 of these transducer header units annually for a variety of pressure sensing applications. The present design is composed entirely of stainless steel. The costs of machining and the difficulties of electrically insulating the leads passing through the header during fabrication keep the cost of production between $10 and $12 per unit depending on the specific application.

The two design alternatives presented in this paper are attempts to decrease the costs by three objectives: 1) minimize the total amount of stainless steel used in the part; 2) reduce or eliminate machining costs by using off the shelf items with little or no required machining; and 3) eliminate insulation difficulties during fabrication by using injection molding techniques. Since only the first objective is easily quantified as a mathematical expression, total volume of stainless steel is chosen as the objective function. This value is obtained directly in the results interpretation module of ANSYS.

Design I uses stainless steel washers/disks as the top and bottom surfaces of the header with "plastic" material making up the interior.

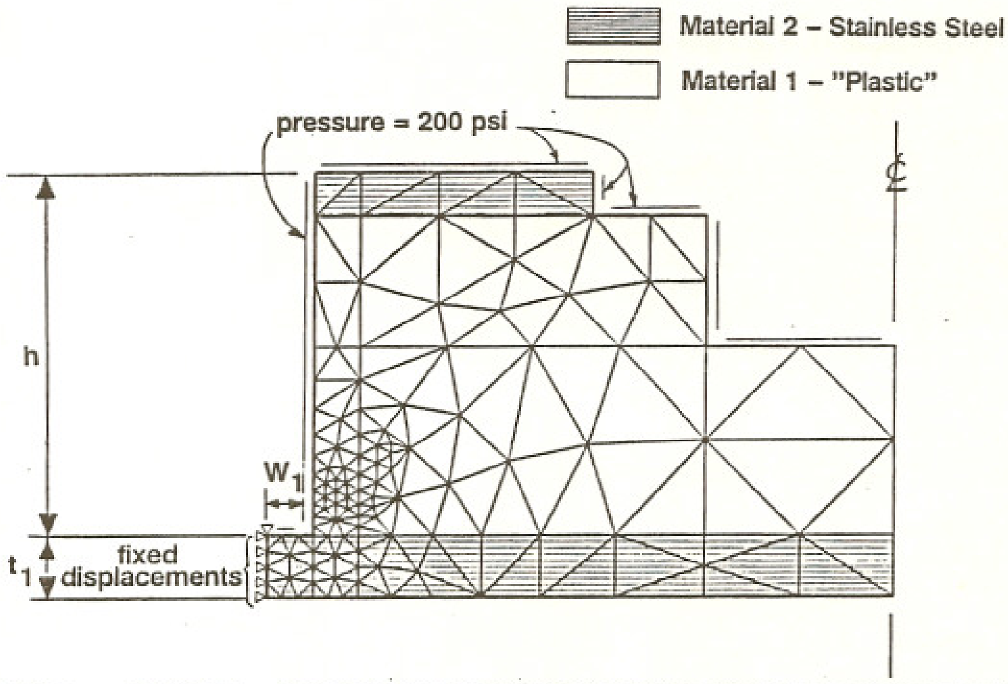

FIGURE 3: DESIGN I: – STRESS ANALYSIS BOUNDARY CONDITIONS AND LOCATION OF DESIGN VARIABLES

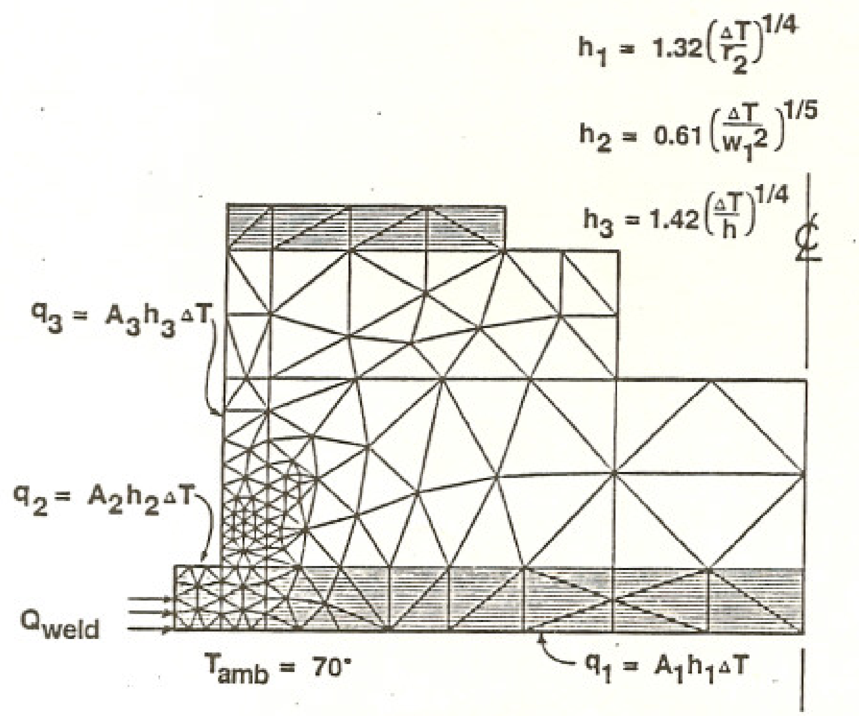

FIGURE 4: DESIGN I: – THERMAL TRANSIENT BOUNDARY CONDITIONS

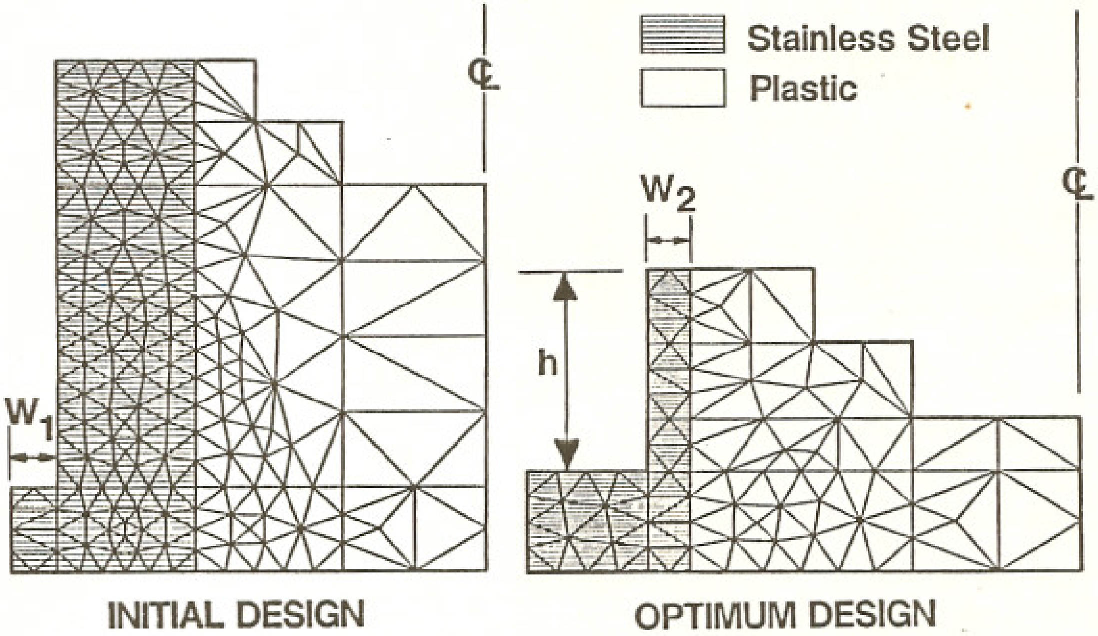

FIGURE 5: DESIGN II: – INITIAL AND FINAL MESHES SHOWING DESIGN VARIABLES

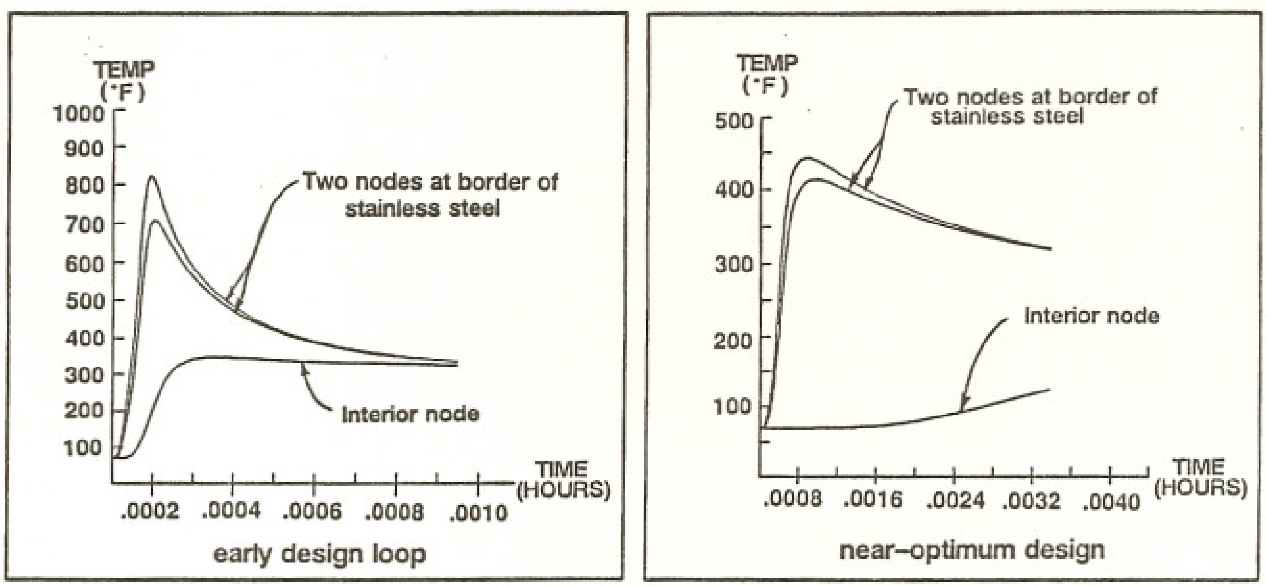

FIGURE 6: THERMAL TRANSIENT HISTORIES FOR PRESSURE TRANSDUCER OPTIMIZATION: TEMPERATURE OF PLASTIC

Since these may be stamped, machining operations are minimal. Figures 3 and 4 show a radial (axisymmetric) section of this design with the finite element mesh, the stress analysis boundary conditions, the thermal analysis boundary conditions, and the three chosen design variables.

Design II, shown in Figure 5, is significantly different than the first; the standard part being built upon in this strategy is stainless steel tubing. Machining operations are reduced to forming the flange for welding purposes. The interior is totally injection molded, thus eliminating much machining and preventing the insulation difficulties experienced with the present design. The design variables chosen for this design are indicated in Figure 5. The finite element model from design I required only minor modifications to be used for this analysis.

The design conditions for the header are twofold. First, the assembly must withstand twice the rated design pressure without exceeding allowable stress values for either material. Secondly, the "plastic" compound must not melt, debond, or deform during welding to the stud. The coefficients of thermal expansion of both materials are sufficiently matched so that thermal stress conditions need not be addressed. The design conditions require two separate analyses; a transient thermal analysis and a static stress analysis. The analyses are solved back-to-back within the optimization loop using the same finite element model, changing boundary conditions and element types from structural to thermal. Six node isoparametric elements are used for the analysis. The constraints defined for both designs were defined as follows: Maximum tensile stress may not exceed 16,000 psi in the stainless steel or 5,000 psi in the "plastic"; corresponding allowable compressive stresses are 24,000 psi and 17,000 psi, respectively. The maximum shear stress at the boundary of the two materials may not exceed 2,000 psi. The maximum temperature that may occur in the "plastic" material during the thermal transient (from welding) is 500°F.

This example illustrates some very powerful capabilities associated with the present method. First, the ability to solve both a transient heat transfer problem and static stress analysis within one design loop makes it possible to impose temperature constraints and stress constraints in a very straightforward, direct manner. Secondly, this design study illustrates how the parametric input capability makes the present analysis possible over relatively large changes in geometry. Parametric input is used to define the mesh density, the approximate time for the thermal transient to pass, and the time stepping increment used for solution.

The parametric definition of the mesh produces acceptable meshes throughout the analysis. Figure 5 shows finite element meshes for the initial and final model for design II. The same commands produced both meshes. Parametric definition of the thermal transient time in terms of the design variables accounts for varying transient durations with material thicknesses, and defining the time increment in terms of the mesh size prevents numerical instabilities during the transient solution. Figure 6 shows transient time histories for three points within the plastic for an early design loop and a design loop near optimum. Note that the peak temperatures and the end of the transients occur at significantly different times.

Because this analysis is quite non-linear and requires substantial computation within a design loop, the computational effort is intensive. The computer times required for design I and design II were 6.5 and 10 hours respectively. The finite element analysis models were generated in one man-week of engineering effort. The starting designs and optimum designs for both design strategies are summarized in Table 1. Substantial weight reductions were achieved in both optimizations.

TABLE 1: PRESSURE TRANSDUCER HEADER OPTIMIZATION RESULTS

PARAMETER	DESIGN I		PARAMETER	DESIGN II	
	INITIAL	OPTIMUM		INITIAL	OPTIMUM
W_1 (in)	0.04	.150	W_1 (in)	0.04	0.09
t_1 (in)	0.05	.04	W_2 (in)	0.08	0.03
h (in)	0.75	.47	h (in)	0.75	0.162
$^{+}\sigma_t$ max_1 (psi)	23800	970		248	1110
σ_c max_1 (psi)	22300	3160		541	1900
σ_t max_2 (psi)	1770	14400		11800	10700
σ_c max_2 (psi)	7930	15100		6180	15300
$(\tau\ max)_{1-2}$ (psi)	825	1005		35	118
T_{max} (°F)	777°F	426°F		434°F	500°F
$Volume_{S.S.}$ (in^3)	.0360	.0247		.1466	.0309
Weight Reduction		-31%			-79%
No. of loops		18			23
*Total CP time		6:29:46			10:03:20

*On VAX 11/780

+Subscript 1 denotes stainless steel, subscript 2 denotes plastic

No overall costs savings can be explicitly defined at this time since neither design concept has gone into production. The design engineer and manufacturing engineer from Company "ABC" estimate the cost of manufacturing for either option to be from $5 to $7 each. Using the higher figure, this translates into a $3 minimum cost reduction per unit, or $600,000 per year at current production levels. Additional cost reduction is realized by reducing the amount of prototyping necessary to come up with a workable design. Although the cost saving is not due entirely to the material minimization realized from the ANSYS runs, the method used was instrumental in obtaining the optimum feasible design.

CONCLUSIONS

A design method combining finite element and optimization technology has been presented. The technique is appropriate in design situations where design costs and analysis costs are high due to repetitive redesign cycles, when potential cost reductions in the product are substantial, and where physical testing of prototypes can be reduced by prior analysis.

Two examples were presented which illustrated how the techniques are applied to physical problems and the potential cost savings that could be achieved in each of those cases. The design engineer must be aware of the potential of this method and make an evaluation as to what benefits could be realized by its use in his design environment.