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Structural Optimization of Landing Gears Using STARSTRUC

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ABSTRACT

The impact of structural optimization is growing in many industries due to economic pressures demanding efficiency in the design process. This efficiency implies developing products which are cost effective and ahead of the competition at the same time. The motivation of the present work is to provide the structural design engineer with tools of optimization techniques and practices that have been applied successfully to landing gears.

Modern landing gears have to meet a multitude of landing and ground handling design loads whose magnitudes are several times the gross weight of the aircraft. All the design loads have to be investigated and their effect on each component must be evaluated. Furthermore, the response of the landing gears to all the design loads must be constrained to satisfy the design requirements while minimizing its structural weight. The weight of the landing gear is becoming an ever more important factor, as inefficient design can add unnecessary weight to the aircraft and, consequently, decrease the payload or useful load.

Typical design examples of components of landing gears are presented that demonstrate the performance of STARSTRUC as an effective weight optimization design tool. The minimum weight design is achieved when the landing gear is subjected to behavior constraints on stresses, deflections, buckling, and frequencies of vibration.

IN THE ENGINEERING DESIGN of a structure, there are always two conditions to be satisfied:

a) The structure must perform a given function
b) The overall cost should be minimum

Traditionally, performance is considered satisfactory when the structure carries the imposed loads safely and generally behaves in an acceptable manner under all expected conditions. The structural behavior is usually determined using the finite element method of analysis, which for most structures is not unduly difficult and has been successfully automated.

At the present time, the engineer is also becoming concerned about how his work relates to its environment. It is now recognized that it is the engineers' responsibility to ascertain that his creations are not only structurally sound and aesthetically pleasing, but also environmentally compatible. All these aspects should be considered necessary conditions for satisfactory performance. As the engineer is now largely freed from the onerous task of manual analysis, it is hoped that he will apply more of his creative energies and judgment to aesthetic and environmental concerns.

While condition (a) above is primarily a problem of analysis, condition (b) is one of synthesizing the structure which satisfies the given performance criteria at a minimum total cost. Today this is by far still mostly trial and error procedure, that is, a small number of possible solutions are synthesized and analyzed for satisfactory behavior, then the most suitable one is selected. The resulting structure will perform the required function safely, but not necessarily at the minimum cost. A highly efficient technique for structural optimization therefore remains the goal of many researchers.

Ideally, an optimization technique for structures should be a computer-based procedure using as input a set of commands very similar to the existing analysis software, and another set specifying the the design requirements. The output of this technique should be the optimum design preferably in printed, plotted, and drafted form. No time-consuming preliminary design by the engineer should be required. The engineer may desire some interaction with the computer to allow him to study the effect of changes in the overall configuration, but otherwise, the procedure should be fully automated. Above all, the procedure must be economical, and better yet in a desktop computer if the size of the structure is not a deterrent.

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The criteria for optimality is minimum cost, both for design and manufacturing. Structural optimization reduces the design cost due to the elimination of the manual trial and error. The manufacturing cost is also reduced because it is nearly proportional to the structural weight. It is therefore reasonable in structural engineering to assume that minimum weight represents minimum cost as the criteria for optimality. This assumption is valid provided that designs which would be unusually expensive to manufacture are avoided.

It is realized of course that for certain types of structures, such as airframes and landing gears where a premium is attached to the weight, structural weight may affect the total cost and performance very decisively. The landing gear and its support structure weigh from 3-8% of the aircraft weight. Therefore on a typical transport aircraft, a 20% increase in the landing gear weight could cost 3-4,000 lbs. weight - the equivalent of 20 passengers. The motivation of the presented paper is to provide the structural engineer with tools of optimization techniques and practices that have been applied successfully to landing gears.

DESIGN PARAMETERS

In 1964, the concept of a design parameter hierarchy was outlined by Schmit and Mallet, [1]*. In their view, the hierarchy consisted of:

1-Type of structure
2-General arrangement
3-Material
4-Geometry of the structure
5-Size of the elements

At one time, it seemed that an algorithm for structural optimization could be developed to treat all the above five parameters as design variables. However, attempts to incorporate variables from the first two categories have been rare, and the few results are not of much help to the practicing engineer. One such example is work done by Michell, [2], who proved that the absolute minimum weight design for a simply-supported beam would be as shown in figure 1.

It is hoped that artificial intelligence will eventually be used to optimize for the first two categories. This may be achieved through a heuristic approach of identifying the strain energy density or stress density of the structure of each finite element type at each load case. However, this will require a tremendous effort to develop such a huge database.

Schmit and Mallet illustrated the concept of design parameter hierarchy by using a three-bar truss where the member areas, the member directions and the member materials were all considered to be design variables. By including variables from categories 3, 4, and 5, they identified the main problem that arises when too many types of design parameters are included. Generally, the rate of convergence is much slower. In the case of the three-bar truss, over 100 design iterations were required to achieve a reasonably accurate solution.

In comparison to the wealth of experience with element sizes in structural optimization, the experience with the geometric optimization of structures is still very limited, [3,4]. This is due to the fact that true geometric optimization requires the differentiation of the structural matrices with respect to the nodal coordinate vector. Development of a general purpose geometric optimization software that can be economically used is presently questionable. Therefore, research into structural optimization has tended to center on the last design parameters, i.e., the size of elements. This approach has been extremely successful with an appreciable weight saving of up to 40% in just about 4 to 6 design cycles for most structures [5,6,7,8].

STRUCTURAL OPTIMIZATION METHODS

It is realized that describing the many optimization algorithms is beyond the scope of the presented work. Many books have been written to this present subject. One of the best books that has been written by Fox, [9], in 1971, lays the ground work for structural optimization, and remains a pioneering work for introducing this subject. Later, papers were published by Venkayya [10], and Schmit, [11], that summarized the statement and the solution techniques of the structural optimization problem.

The design variables are defined as those quantities that are changed during the iterative procedure which seeks an optimum. These N real numbers are conveniently written as an N X 1 vector of the design variable D. Recognizing that only a single scalar can be optimized at a time, one must devise a performance index, such as the structural weight W which is a single-valued function of D. W can always be chosen such that the goal is:

$$W(D) \longrightarrow \text{Minimum} \qquad (1)$$

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* Square bracketed number refer to references at end of paper.

The search for the optimum must be carried out in an N-dimensional design space populated by M barriers, which quantify the applied contraints. Because engineers usually respond to analysis results by saying such comments as: The stresses are too high, the structure is flexible and the deflection is too large, the frequency is too low; this suggests that structural performance can be formulated as M functional in equalities:

$$G_m\ (D)\ \geq 0 \text{ for } m = 1,2 \ldots\ldots M \qquad (2)$$

The mathematical programming methods, generally called the "search" or the "direct" methods, seek the optimum by making controlled incremental changes to the design variable vector, basing the magnitude and direction of such changes on certain properties of the objective function, the constraints and their gradients.

The optimality criteria methods, essentially using an energy approach, establish a functional for the structure. The first order stationary conditions of the resulting functional in the design variable space yield the optimality conditions for the optimum design of the structure under the specified constraints.

The above mentioned two methods are now comparable not only in their efficiency, but also in their basic concepts as pointed out in [12].

LANDING GEAR DESIGN

A landing gear by definition, can be any device that supports the aircraft during a landing or a take-off. The design of landing gears has grown in complexity since the introduction of skids of the 1903 Wright Biplane. During World War I, aircrafts had shock absorbing landing gears, which used rubber rings around the axles where they attached to the support struts. Oleopneumatic shock absorbing struts were in use by 1918. The name Oleopneumatic refers to the use of the aircraft hydraulic oil in combination with air. Retractable landing gears were generally introduced in the early 1930's. Since that time, landing gears have become more and more complex, primarily because of the increased demands imposed upon them. As an example, the Lockheed C-5A presented a major challenge for the design of its landing gears that supports a weight of 732,500 lb. This requires many wheels and relatively low tire pressure. Furthermore, drag requirements precluded large landing gear pods, therefore complex retraction mechanisms were developed to stow the huge gear in a low-drag envelope. Obviously the weight of such a landing gear combined with its structural integrity represented a major design challenge.

As shown in figure 2, a typical landing gear consists of shock absorbers, wheels, tires, brakes, linkages, steering systems, and provisions for jacking and towing.

Modern aircraft landing gear assemblies can be classified into two basic types:

a) the cantilever
b) the tri-pod.

Cantilever configuration landing gears operate in a telescope action of a piston-axle component inside a cylinder and/or housing. This shock strut assembly type is of course not a true fix-ended cantilever structure as the strut is braced for reaction to tire/wheel transverse loading. The brace being either a separate truss member or integral with the housing. See figure 2 for illustrations of the cantilever type landing gear.

The tri-pod type of landing gear configuration is as the name implies. Three strut members apex approximately in the wheel-axle centerline intersection thus providing good stability for all directions of tire loading. One member of the tri-pod is designated the shock absorber.

Due to the complexity of the landing gear structure and the crucial importance of its reliability and structural integrity, the design decision process is generally very complex and iterative in nature. Among the factors that govern the design of a landing gear are the load paths, the degree of indeterminacy of the structure, and the material selection. Structural indeterminacy and load paths are intertwined in that one usually leads to the other. An indeterminate structure is one in which there is more than one path for a load to take. The load paths of a landing gear are generally a function of the following two factors:

1-Relative stiffness of the structural components, i.e. the stiffer component reacting proportionately more load than the less stiff component.
2-The socketing action between the different components such as the piston movement inside the cylinder which is socketed inside the housing.

Another important factor in the design of a landing gear is the number of loading cases, perhaps as many as 20, that have to be examined.

The analysis of that many load cases, even for a simple design, can be a very time-consuming process. Realizing this point, and at the same time emphasizing the importance of its structural weight demonstrates the real benefits of introducing structural optimizaiton as a design tool. Among the immediate advantages that follow the use of structural optimization are the following:

1-With a software such as STARSTRUC that can handle multiple static, stability, and vibration constraints simultaneously, the design engineer can use these features to produce more reliable structures.

2-With the design engineer freed from the guess work of the trial and error, he can concentrate on more creative ideas such as simplifying the load path or examining the effects of different material selections.

3-The ability to develop more complex finite element models to obtain more accurate results such as expanding the model from simple beam type model to a model that includes shell or solid elements.

NUMERICAL EXAMPLES

In this section, examples are presented to demonstrate the efficiency and generality of the approach used in the presented program.

EXAMPLE 1-This example represents a simplified 2-dimensional landing gear as shown in figure 3. This simple model is selected as a test problem, that can be checked by hand calculations, due to the fact the this is the first time an optimization algorithm is applied to a landing gear and no published work is available for comparison. The initial design variables are selected as follows:

1-First design variable is a tube with O.D./I.D.=3.5/2.9 in. for beam number 1.
2-Second design variable is a tube with O.D./I.D.=4.5/3.826 in., for beam numbers 2 and 3.
3-Third design variable is a tube with O.D./I.D.=5.563/4.813 in., for beam number 4.
4-Fourth design variable is a rectangular section with dimension .5 X 3. in., for beam number 5.

Two design cases are presented and these are:

1-Case A: All elements are made of steel alloy with the following data:
-Modulus of elasticity = 29E6 psi
-Density = .283 lb/in^3
-Allowable stress = 100 ksi

2-Case B: Material of the drag brace, element number 5 is changed to Aluminum alloy with the following data:
-Modulus of elasticity = 10E6 psi
-Density = 0.1 lb/in^3
-Allowable stress = 50 ksi

Both cases converged in one iteration with a weight savings of 34% as shown in Table 1. It is interesting to note that initially, the critical buckling load for the drag brace is much lower than the allowable stress. Therefore, STARSTRUC designed this element for local buckling.

EXAMPLE 2-This example represents an idealized drag brace with geometry and loading as shown in figure 4, and modelled with 44 flat shell elements. Six design variables are used to represent the six plate thicknesses as shown in figure 4. The objective of this example is to achieve the minimum weight of the following proposed configurations:

1. Case A: No Cutouts
2. Case B: One Cutout: Elements 20, 21, 24 and 25 are eliminated.
3. Case C: Three Cutouts: Elements 8, 9, 12, 13, 20, 21, 24, 25, 32, 33, 36, and 37 are eliminated.
4. Case D: One Big Cutout: Elements 8, 9, 12, 13, 16, 17, 20, 21, 24, 25 28, 29, 32, 33, 36, and 37 are eliminated.

The above four cases are optimized with stress and buckling constraints with the following design data:

1-Initial thickness of all six design variables = .25 in.
2-Material density = .283 lb/in^3
3-Poisson's ratio = 0
4-Modulus of elasticity = 29E6 psi
5-Allowable normal stress = 25 ksi
6-Allowable buckling load factor = 1.2

To our knowledge, there is no published work available for similar configurations. Therefore, it was decided first to solve a complete rectangular plate with dimensions 6 X 36 in. using the above data. The buckling load factor of the initial design as calculated from STARSTRUC is 1.7339 which compares favorably with the analytical solution of 1.7254 calculated from Euler's buckling formula. This demonstrates the accuracy of the presented approach. The results of optimized configurations are shown in Table 2. It is interesting to note that in all four configurations, STARSTRUC takes two design iterations to converge to the minimum weight design. This demonstrates the efficiency of the presented optimization algorithm.

This example can also be considered as a way of handling geometric optimization where the design engineer can change the geometry of the structure, and then optimize each configuration. In this case, the experience of the design engineer coupled with the presented approach can lead to the best configuration.

CONCLUSIONS

This paper is an attempt to provide the design engineers with basic understanding and confidence of this valuable tool of structural optimization. STARSTRUC has been used with the obvious results of material savings on critical components such as the landing gears. Furthermore, with such a tool the design engineer does not have to spend valuable engineering time performing trial and error procedure of the finite element method of analysis.

The understanding of the upper and middle management of this tool and its benefits is crucial to expanding the usage of structural optimization especially in the aircraft industry where it is needed the most. It is expected that structural optimization will become a standard procedure in the design process. Next, structural optimization should be integrated with the other existing tools of the design process with the purpose of increasing the efficiency of the whole engineering industries.

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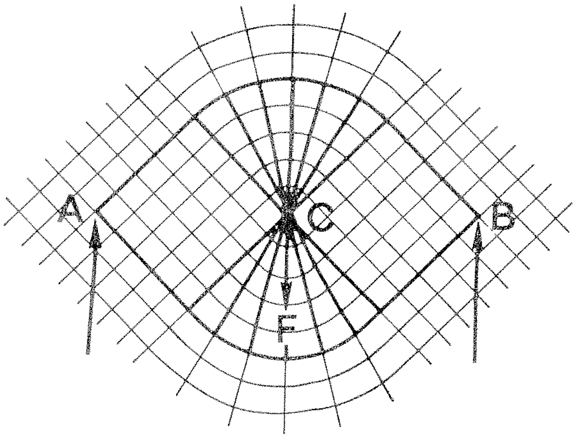

FIGURE 1.
Michell's Simply-Supported Beam
with a Central Load

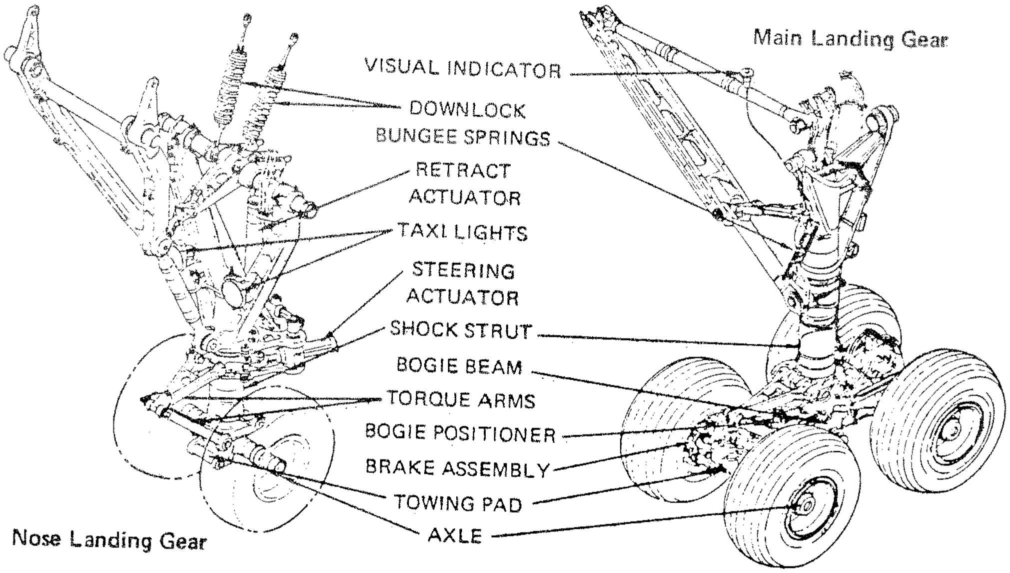

FIGURE 2.
L1011 Landing Gear
Courtesy of Author of Reference [13]

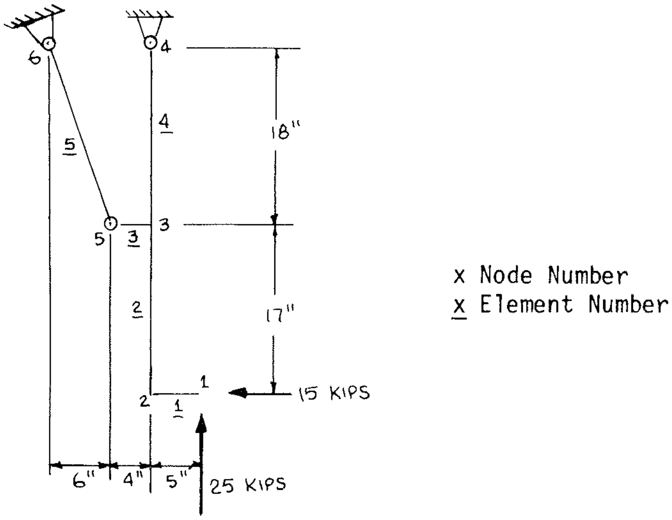

FIGURE 3.
2-Dimensional Landing Gear

TABLE 1.
Optimization Results of Example 1

Design Variable No.	Element No.	Initial Value In.^{2}	Final Values In.^{2}	
			Case A	Case B
1	1	3.02	1.843	1.843
2	2-3	4.41	1.786	1.786
3	4	6.11	3.140	3.140
4	5	1.50	2.486	7.209
TOTAL WEIGHT (LB)		64.45	42.56	42.89
NO. OF ITERATIONS			1	1

Design Variable Numbers

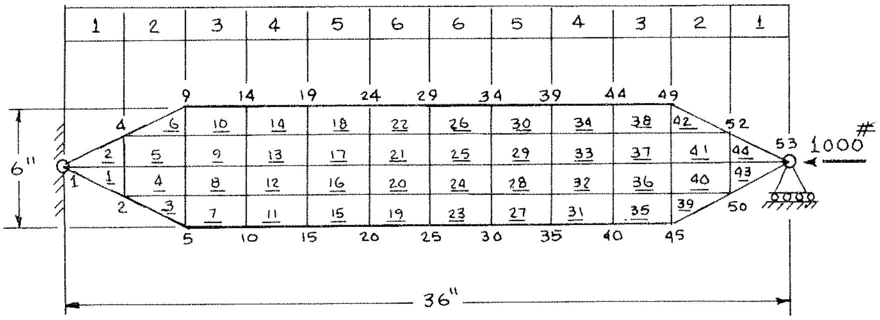

FIGURE 4.
Drag Brace Model

x Node Number
x Element Number

TABLE 2.
Optimization Results of the Drag Brace

Design Variable No	Optimal Thickness Distribution			
	Case A	Case B	Case C	Case D
1	.1671	.1553	.1518	.1495
2	.1924	.1753	.1704	.1659
3	.2043	.1922	.2725	.2646
4	.2217	.2204	.2959	.2877
5	.2296	.2378	.2234	.2970
6	.2335	.3271	.3111	.3012
Initial Weight (lb.)	12.74	11.46	8.914	7.641
Final Weight (lb.)	10.95	10.03	8.445	7.509
No. of Iterations	2	2	2	2