

## THEORETICAL FORMABILITY

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The major problem facing the aerospace industry today is the production of airframe components that meet the demands of increased environmental conditions. Significant is the cost of the newer metals. Added to this is the drastically reduced lead times required from engineering conception to delivery of the completed article. This problem becomes more acute when one realizes that very seldom is complete fabrication design data available for the engineer, and that the amount of funds available to develop design and fabrication information is greatly limited. These alone create a major problem, but we must not overlook the increasing complexity of the overall airframe structure.

The airframe industry needs to advance the state of the art for design fabrication using the new metals. To design and fabricate structures without sufficient data will only result in excessive scrap, inadequate tooling, and excessive handworking. "Theoretical Formability" provides the most direct means for solving the overall problem, and it is a must. It is simply an analytical method for predicting the forming limits of sheet metals using the properties of the materials. It directly provides verified fabrication design data in a very short time.

Let us take a look at some of the factors influencing the development of "Theoretical Formability." The exponential increase of material costs from that of the World War II aluminums to the space age refractories is important. It is evident that metals that will be fairly common in airframes five years from now, such as columbium and beryllium, have a cost increase over aluminum 300 and 500 times respectively. The material cost picture plus the great increase in application of the new metals forecast for the next decade, will have a tremendous influence on fabrication costs. In the Aerospace Industries "Trends Forecast," a survey conducted among airframe manufacturers has indicated the general materials usage for the next ten years. This survey showed that use of the super alloys and refractories relative to the aluminums and steels in 1960 was only 5 percent, but an increase to 30 percent was predicted by 1970. By multiplying the average cost of the super alloys and refractories at \$50 a pound for sheet materials, and their relative usages for 1960 and 1970, comparative cost factors for the three basic materials can be obtained. Although the super alloys and refractories produce only 50 percent of the total costs in 1960, they will contribute 90 percent of the total structural material costs in 1970. It can be realized that any saving in material, that can be gained by proper design and thus reduce scrappage, can be very significant.

Let us briefly review what has been done, to understand the forming of sheet metals, and review the progress made in the past two decades. We can divide this into two basic categories: (1) the practical experimentation type of forming development as evidenced by "cut-and-try" shop operations, and (2) the purely theoretical work accomplished by various universities and governmental agencies. Most of the work performed during, and immediately after World War II was on forming aluminum and magnesium. Practically all of this work was sponsored by the National Defense Research Council and the War Production Board. During the early fifties, very little work was accomplished. It was not until emphasis was placed on solving the problems associated with fabricating the titanium alloys, that industry realized that existing information was not adequate, and a major effort was initiated under the direction of the Office of the Secretary of Defense.

During all of these formability development years, there remained a cleavage between the purely theoretical and practical experimental type of work. Although considerable work was done by individuals in our universities and research centers in basic research very little practical application, specifically relating theory to shop practice, had been accomplished. To establish a relationship, a study was conducted to find the correlation between a metal's properties and processes to form it. The results of this study was the development of "Theoretical Formability." This concept "bridges the gap" between theory and shop. Two typical airframe parts are shown in figure 1 with their respective formability limit graphs in terms of the part's geometries. They are rubber formed stretch flange parts representative of bulkhead sections and deep drawn cylindrical cups. The graphs represent the geometrical limits of the particular parts for a given material. Other materials will have similar graphs. Parts with geometries falling outside the formability envelopes will fail during forming by either buckling or splitting. Those falling within the envelopes will form successfully. Limit graphs such as these can be developed for all forming processes and materials.

Actually there is nothing mysterious about "Theoretical Formability." Basically there are eight major steps necessary to develop formability equations. The procedure depends upon a thorough understanding of the forming process so that the parts and processes can be analyzed and the failure types determined. Then by determining the part geometries that relate to the failures we can develop the general failure limiting equations. Next, the equation is graphically portrayed, sample parts are selected and formed to empirically establish the position of the curve. At this point we will have established and verified a limiting curve for one process and material. We next establish a means to relate the properties of one material to another. These relation factors are called formability indices. Once these are established and verified, we can establish the position of curves for other material. Our last step is to finalize the equations into forms so that correlations between one material and another will be valid for selected geometrical and property parameters. Most important and this cannot be emphasized too much, these steps need to be done only once for each process. For a clearer picture let us take a specific part and process and step by step show the sequence and procedure used. As an example, let us consider deep drawn parts. The first step is to completely analyze the process and establish the major types of failures that will be encountered. For deep drawn parts, failure is evidenced by wrinkling of the flange due to compressive stresses applied to the part during forming, and splitting at the sides when the material is strained to the point that the metal separates. These failures are interdependent for this process and have to be considered together.

Next, we consider the part geometry and establish a relationship between the geometry and the types of failures for the process. In deep drawn parts we find the geometries of original blank radius  $R_0$ , material thickness  $t$ , and part depth  $h$  are the primary ones.

These geometrical parameters will make it possible to develop equations that are a function of the geometry. The next step is to establish the basic equation of mechanics for the type of failure in terms of the part geometries. In considering buckling we find the basic equation for the critical buckling stress of the part is a function of the material stiffness, its deformation characteristics and the relationship of the flange height to material thickness. This basic equation is then expressed in terms of the part geometry. In a like manner, splitting is expressed as a function of the amount of ductility or stretch the material has without breaking. Although the general equations can become quite unwieldy, by proper analysis and selection of the primary and secondary variables, the equation can be simplified as shown in figure 2.



# Contrails

Because the equations just shown are not easy to correlate in their present form, they are then plotted on a graph as shown in figure 3. The graph at this stage gives only the shape of the curve, as represented by the equation, and the position of the graph can move as shown by the double headed arrows. This graphic expression of failure relationship, portrayed in terms of the part geometry, is used to select experimental parts to test the theory of the shape of the curve. The parts are formed and plotted to verify a curve for one material, establishing the limits of part size and shape.

The primary work established the shape of the limiting curve for a particular material. The next step is to establish a basis so that we can position the curves for other materials. To do this we will now find the function of the material's properties that will establish a relationship to the part geometries. For splitting failures the significant material property is elongation. In our particular case, elongation is the natural strain established by a 20 thousand gauge length in a tensile specimen. For buckling the ratio of Modulus of Elasticity to the Buckling Stress is the property which will establish the correlation we are seeking. These material properties are used as "formability indices" to relate one material to another as shown in figure 4.

Part shapes are now selected that will establish the position of the new curves for several different materials. The parts of the new materials are then experimentally formed and the results plotted on the graph. The theoretically established indices are then applied to the graph to adjust and establish the position of the limit curves for the new materials. The last step is to finalize the equations as shown in figure 5 that allow us to predict the forming characteristics of all materials for deep drawing. To do this the value of the constants are established in the equations that will be valid for all materials.

The preceding analysis shows that theoretical formability is actually an extension into practical terms of the theories concerning the elasticity and plasticity of metals. Completely new concepts have been developed, however, which are unique in metal forming. Vought Aeronautics has been working under an Air Force contract to extend the concept of theoretical formability to the following twelve forming processes:

Brake Forming	Rubber Forming
Dimpling	Sheet Stretch Forming
Joggling	Andro Forming
Spinning	Deep Drawing
Linear Roll Forming	Rubber Bead Forming
Linear Stretch Forming	Drop Hammer

This concept can be applied to any forming process, including the new high energy rate methods. But for this study, it was decided to apply the concept first to the more conventional forming process. Nineteen materials for formability analysis in the contract were selected to furnish a broad range of properties. This permitted the development of formability indices that can be applied to any metal. All important classes of aircraft materials are represented from aluminum to tungsten. The stainless steels, for instance, include the all-beta and the heat-treatable 6Al-4V; and the super alloys include both the nickel and the cobalt base types.

The current contract has already produced the results that were expected. The program has proven that the initial development of the formability limit equations and graphs are accurate. Not only are the graph shapes correct, but correlations show that the formability indices can predict the position of the graph for each material. This means that

the material properties obtained from simple tests can be used to predict formability limits. A major result of the program is the establishment of composite formability limit graphs. Graphs such as these allow the quick analysis of the comparative formability of the different materials.

Another significant result of the study is the development of design tables for various forming processes. Such information provides design engineers with the maximum and minimum dimensions of parts from various materials.

A third major result of the study is the development of predictability equations for the forming of future materials. These equations relate the geometry of the part to the properties of the various materials. To predict formability of future materials, all that we will need is the material's mechanical properties. These properties can then be substituted into the equations and limit graphs established. Experimental forming of a few parts will verify the graphs and give the engineer confidence in the design tables.

There are several benefits to industry that can be realized by the application of "Theoretical Formability." The development and qualification of design data for the engineer is important at a time when it is required. Within a matter of hours after the engineer has requested design data, preliminary information can be developed solely from the published material properties readily available. This information plays an important part in selecting a material for use by providing quantitative data that eliminates the guess-work. Within approximately 30 days, usually as soon as a limited amount of material can be procured and tested, complete design tables can be established, verified, and published. This information also provides the optimum processing sequence and material usage. Most important, the application of "Theoretical Formability" eliminates the major stumbling blocks such as limited design data, redesigns, improper material selection, and costly scrappage. Another benefit of theoretical formability is better designed parts. The most acceptable material can be selected, and, with a knowledge of the material limitations, it will be possible to design parts with fewer details.

Of major importance to manufacturing is the advantage gained from the proper selection of tooling and equipment required to fabricate the parts designed by engineering. By analysis of the part and material, the right forming process can be picked the first time, the fabrication sequence of temperature and material condition can be selected, and the proper tools with their optimum tooling materials provided. As an example, a part designed by engineering could have geometries that would allow the fabrication of the part by either drop hammer or mechanical die. Our first inclination would be to form by drop hammer from a cheaper tooling standpoint. But by having verified knowledge of the materials forming limitations for each process, we might find the part to be outside the limits for drop hammer and the selection of mechanical die operation, even though the tooling was more expensive, would allow us to form the part successfully the first time. This analysis will also tell us whether we need to form at elevated temperatures or not, and thereby guide selection of tools and tooling materials.

Up to now we have briefly reviewed "Theoretical Formability," its history, applications, and development, and summarized what is currently being done with some of the more direct benefits that will result. Although the work to date is a tremendous advance in basic understanding of forming processes, there still remains several areas in which we need to direct our efforts. The first area is the extension of "Theoretical Formability" to all sheet metal forming processes. The work just discussed under our present contract did not include some of the more complex shapes produced by several of the processes. These parts and processes need to be investigated to completely define each process

and all its applications. Several of the processes currently under investigation still require extension into more complex part shapes. Also there are several of the more conventional processes that have not been studied. As previously stated, this concept can be readily applied to the high energy rate methods, but to do this we need to explore these processes and develop a better understanding of their applications and limitations. We cannot afford the luxury of waiting until these processes are clearly defined through shop "cut-and-try" operations.

By the use of this concept, the tremendous saving in time, manpower, tooling, materials, and leadtime can be readily seen. If we multiply this by the number of prime and subcontractors in this country, this saving is manifold. We believe this is one of the most significant pieces of work being accomplished today. It is not only a break-through in the technology of forming metals but will result in tremendous dollar savings to the Air Force and DOD.

Our future program plans are oriented towards developing more scientific approaches to other metal forming processes and we encourage industry to think along these lines. We welcome your ideas, however, we also urge you to be prepared to provide some evidence of demonstrated feasibility or comparative results that we can more readily determine the merits or potential pay-off of your proposals. I'm sure that you realize we receive many new ideas from many sources. Those which are considered technically sound, and backed up with some evidence of significant improvement in results, have the greatest opportunity for support.

## REFERENCES

1. ASD Technical Report No. 61-191, "Theoretical Formability." Wood, W. W.



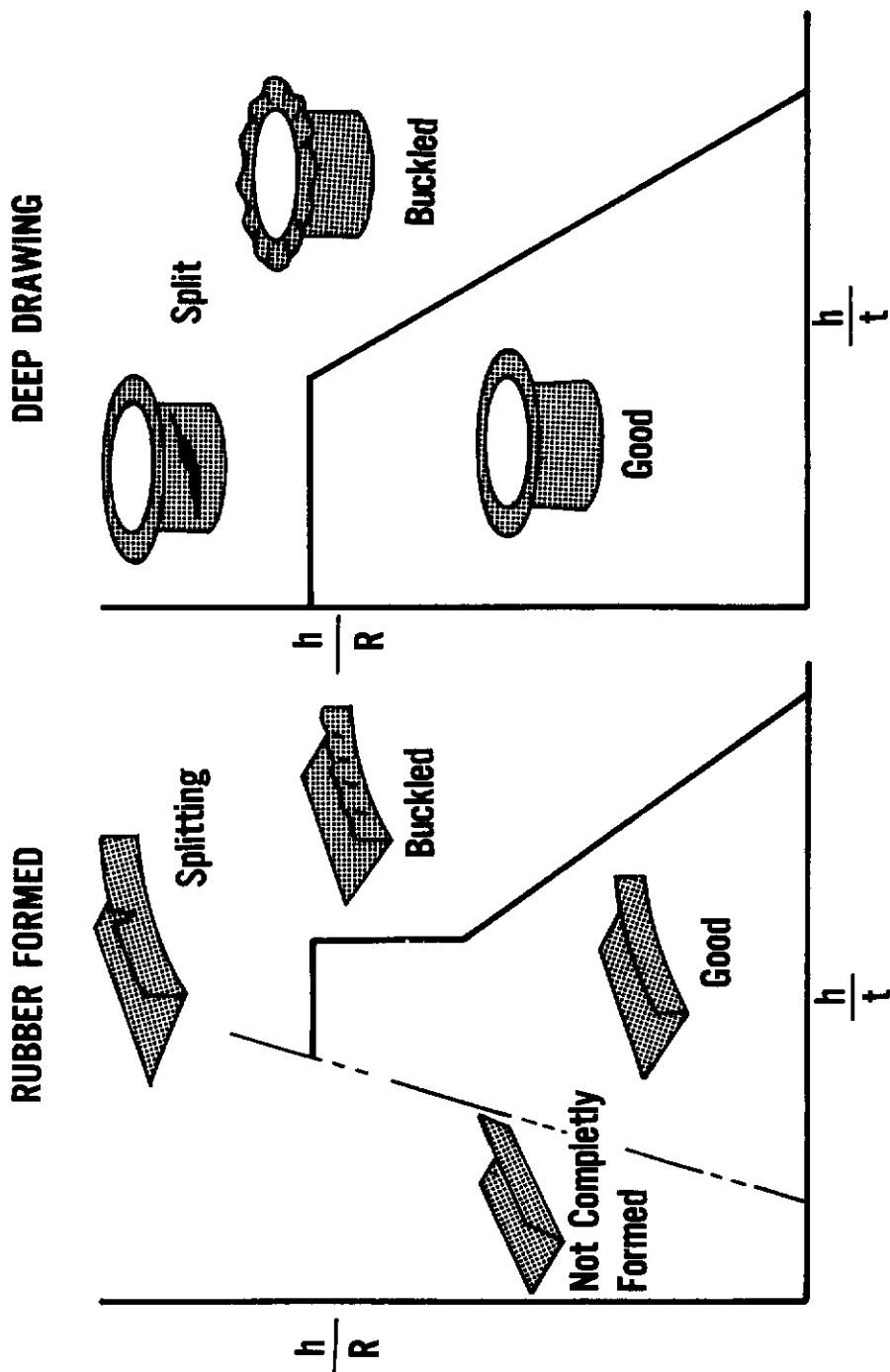


Figure 1. Typical Forming Limit Curves

**BUCKLING**

$$S_{CR} = \frac{K}{R_o^2 t} \left( \frac{Et^3}{12(1-\mu^2)} \right)$$

$$S_{CR} = B \frac{E}{(R_o/t)^2} = f \left( B \frac{h+R}{R_o} \right)$$

**ELONGATION**

$$e = \frac{R_i + h + (R - R_i) - R_o}{R_o}$$

$$e = f \left( C \frac{h+R}{R_o} \right)$$

Figure 2. The Basic Equation

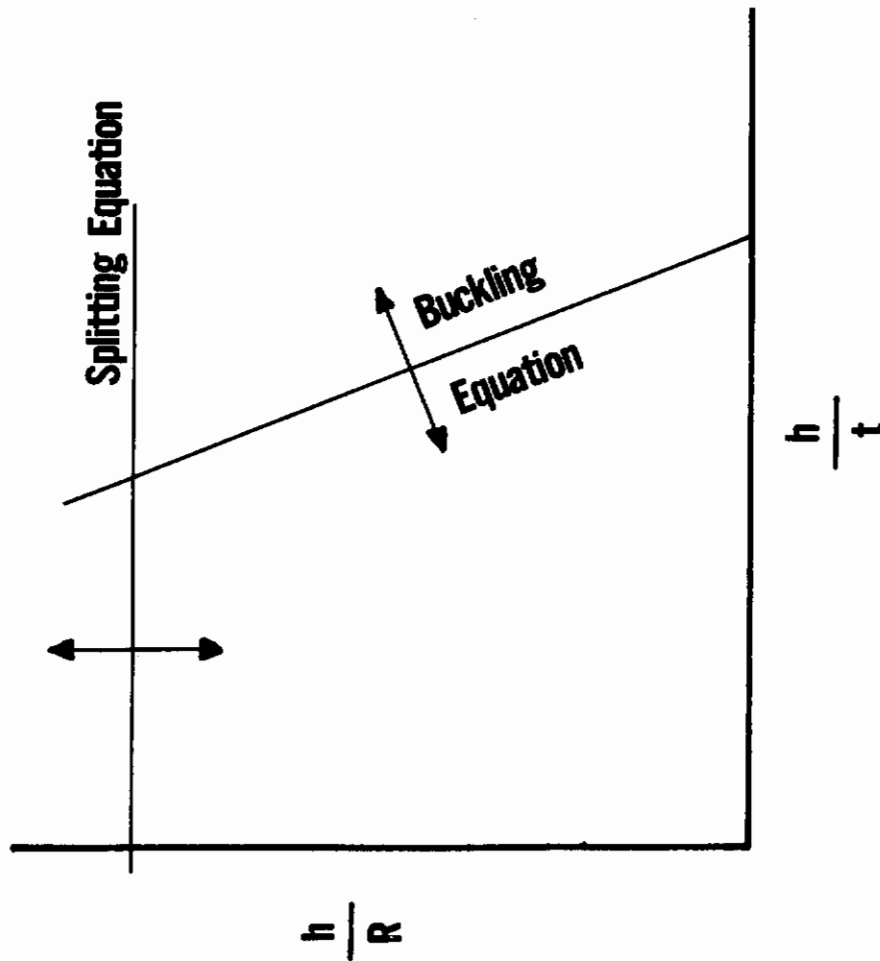


Figure 3. The Graph Shape



**Splitting: Function of Elongation**

$$\frac{h+R}{R_o} = f(e)$$

**Modulus of Elasticity  
Stress to Buckle**

**Buckling: Function of**

$$\left(\frac{R_o}{B}\right)^2 = f\left(\frac{E}{S CR}\right)$$

Figure 4. Formability Indices

**SPLITTING CONSTANT**

$$C = \frac{h+R}{eR_0}$$

**BUCKLING CONSTANT**

$$B = \frac{\left(\frac{R_0}{t}\right)^2}{\left(\frac{E}{S CR}\right)}$$

Figure 5. Deep Drawing Predictability Equations

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