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SHELL INSTABILITY PROBLEMS AS RELATED TO DESIGN

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SUMMARY

A presentation is made which highlights several current shell stability problems. A searching reappraisal of shell stability research is advocated in the light of the current rapidly mounting intensity of shell research which in many cases is disproportionately academic and non-design orientated.

INTRODUCTION

In scanning the list of participants in this symposium one can only marvel to see that so many serious investigators in the field of elastic stability can be gathered at any one time. Likewise, the papers presented cover a cross section of the important recent works being accomplished in the field of shell stability. At such a distinguished gathering, however, the responsibility of pointing out areas which are not receiving sufficient emphasis, is of equal importance to the task of reporting accomplishments. It is the hope of the authors that in pointing out specific problem areas and, where possible, indicating their relative importance in the design process, that interest will be aroused and solutions be expedited. Contrary to what has quite often become the expected plea, this paper will not ask for more effort in the discipline of shell instability, rather a diversion of the serious worker to the problem areas offering a maximum return potential. Even a casual glance at Figure 1 would indicate the widespread interest in shell stability as evidenced by the increase in the quantity of literature being published on shell analysis. Unfortunately much of it is concerned with peripheral problems and much deals with trivia. Perhaps it was this inundation of mediocre and inconsequential papers that prompted the editorial board of the Journal of Applied Mechanics to adopt a policy which excludes from consideration, without review, papers in the field of shell stability which employ small deflection theory or otherwise apply established techniques to the solutions, "no matter how interesting," (reference 3). While not a deterrant to all, at least such a policy will discourage waste effort involving trivial refinements and mathematical gymnastics. In the face of a limited and inexpandable supply of competent talent we must turn our attention from the inconsequential problems to those where increased knowledge and analytical techniques hold promise of increased structural reliability and efficiency.

DESIGNING FOR STABILITY

A missile or spacecraft is primarily a pressure sustaining structure. Perhaps in excess of 90% of the structure may be sustaining pressure loads. In the early missile designs most shells were pressure critical and stabilization was not necessary except for certain handling conditions. However, as material applications and properties have advanced, wall thicknesses have diminished until today many shells which have been previously designed by pressure vessel criteria are now at or beyond the threshold of the instability problem. Figure 2 represents a design problem involving a solid propellant motor case which illustrates this situation. The case, a second stage sustainer, is subjected to axial compression and bending loads during the initial boost stage. After first stage booster cut-off the sustainer is fired and the case is subjected to an internal pressure condition. Figure 2 shows the required wall thickness of this 18-inch radius, steel cylindrical shell versus the tensile stress of the material considered. For the condition of internal pressure the typical hyperbolic relationship is obtained. However, consideration of the condition which induces compression in the shell establishes a lower limit of wall thickness which can be drawn as a horizontal cut-off line. This cut-off line, when derived for an unsupported shell by the method of reference 4 intersects the hyperbola at an ultimate tensile stress of 251,000 psi. This approaches very closely the ultimate strength of the material selected for the motor case. Thus it can be seen that additional improvements in the strength of case materials would be pointless without something being done about the shell stabilization problem.

Where previously it was conservative to neglect core stabilizing effects they now are a first order consideration. Figure 2 shows two additional cut-off lines. The intermediate one is based upon the work of Seide on cylinders stabilized by elastic cores (reference 5) and the lower one is based upon a value obtained in a full-scale compression test of a motor case filled with inert propellant. If the case were designed to the lowest cut-off value a weight saving of approximately 40% would result. These particular values of the limitations due to compressive instability are cited merely to illustrate the problems rather than define actual allowables. Methods of predicting stabilizing-effects of viscoelastic cores are rather difficult to apply in practice. For example, in applying Seide's theory it was necessary to assume a value for the modulus of elasticity of the core. This is difficult to obtain, as it is well known that core materials behave in a viscoelastic manner and any test program must realistically account for the actual temperature and strain rate if it is to be an acceptable analog of the operational problem. Here then is a fertile field of investigation.

STIFFENED SHELLS

The designer, faced with the problem of shell instability must ask, "why monocoque?" It is well known that, except for the limiting cases of minimum-gage handling problems and thick-walled shells the monocoque is structurally the least efficient mode of material disposition for non-stabilized shells in compression.

In general, then, it behooves the designer to either avoid monocoque or stabilize it wherever possible. Some methods of avoiding monocoque include the following construction:

- (a) Conventional frame and/or stringer combinations
- (b) Integral stiffening
- (c) Sandwich construction
  - (1) Isotropic core (e.g. foam)
  - (2) Orthotropic core (e.g. honeycomb)
  - (3) Unidirectional core (e.g. corrugations)

The integrally stiffened shell is illustrated in Figure 3 which shows a machined waffle pattern that has been successfully used for design of several cryogenic fuel tanks. This simple configuration at first represented a fabrication challenge. Now that it has been successfully produced for several designs, attention has been given to optimizing the stiffener configuration. Interestingly enough, the most difficult problems here are not those concerned with optimizing the shell for strength only, but rather optimization consistant with the conditions imposed by manufacturing limitations and other design considerations.

Figure 4 shows a weight comparison of several systems of construction for cylinders as a function of loading intensity for an actual design case involving combined axial compression and bending. Similar consideration is given to spherical caps under external pressure in Figure 5. Here the treatment is more general in that weight, or gage, has been normalized as has the loading. There are several items worthy of note in this figure. First, we find a substantial difference between classical theory for monocoque and the empirical curve based on test data. The empirical curve shown is based upon a constant coefficient of 0.2 in the classical formula. This agrees within 10% with the available experimental data. Further examination of Figures 4 and 5 shows that there is a much larger potential pay-off in attempting to apply sandwich construction to the design problem than there is in operating on the monocoque theory. One problem which looms large in designing for sandwich construction --- especially in cryogenic tankage, is that of thermal stress and the technique of combining thermal stresses with load-induced stresses. A rigorous address to this problem should provide useful information to the designer. An even more pertinent observation is that the weight advantages shown for sandwich construction are often lost in the reduction to design practice, especially in the design of joints and attachments. Thus the question must be raised whether a portion of funds spent on shell research and development could not, in many cases show greater returns, even for the long term, if spent on development of design and fabrication techniques rather than analytical methods. The problems of the stability of stiffened shells afford a propitious interface for the interests of the researcher and the designer and the contributions of both are essential.

SCATTER AND RELIABILITY

One problem of the designer which is even difficult to state, let alone operate upon, concerns the relationship among shell instability solutions, product testing and design factor-of-safety philosophy. In the design and construction of large boosters and space vehicles time and economic considerations dictate that full scale test specimens be few in number; yet the reliability of the vehicle must be close to 100%. Under the circumstances the large scatter in test and performance data experienced under present test techniques and the large deviations from predictions cannot be accepted without unwarranted design weight penalties or reduction in vehicle reliability.

It might be argued that many reliable aircraft were designed with limited full scale testing. It can also be argued however that there were many compensating factors in aircraft design that are not found in missiles. Among these were the sometimes meaningless corrections such as material and coupon correction factors, none of which had much direct bearing on shell instability. Nevertheless these corrections inadvertently provided reliability due to a high induced safety factor. Figure 6 reflects the design of a typical thin shell structure. If only specimen No. 1 had been tested and the design based on this value (e.g. the normal 1.5 safety factor applied to this value) the structure produced would have apparently operated satisfactorily and would still not have failed under limit stress even if an actual strength value as low as specimen No. 6 had been realized. Missile and spacecraft designers however, under pressure to produce more and more efficient structures have been forced to reduce this so called ultimate factor of safety from the standard value of 1.5 to 1.25 and even less. Using this criteria the allowable working stress for the illustrative example would have been raised and the reliability of the production structure, based on this limited test data, would have been reduced to an unacceptable level.

Certainly, there must be a reason for this scatter. Does the observed scatter of test data reflect a variation from specimen to specimen or does the prime variational influence lie in the testing? If the former, perhaps we can control variations by design techniques. If the latter, can we expect similar variations in actual operations? These problems must be answered if the designer is to apply rational reliability criteria to his products. If some of the parameters affecting scatter were known, these data could be reduced to a much narrower scatter band --- even to a reasonably accurate standard value. If this were possible, data from a few tests could be used with greater assurance. Work to reconcile and explain the observed scatter would be most welcome by those of us in the design effort. In any event more rigor must be observed in the reporting of new test data.

OTHER PROBLEMS

Dynamic loading of shells, although not necessarily, or even predominately, a structural stability problem, is another area of great concern to the designer. For the large boosters now in study phases the effects of ground winds, wind shears and gusts, transient thrust and release loads, fuel sloshing and structural cross-coupling and blast exposure loom as first order problems. We feel that these problems are not receiving their proportionate share of attention.

CONCLUDING REMARKS

At the risk of making a presentation - and a short one at that - of perhaps considerably different context than most of those here, we have attempted to expound a philosophy based upon the immediate needs of the design engineer. Certainly we have not covered all important areas. The tremendous increase in the tempo of shell instability research in recent years would indicate such appraisals are periodically necessary if our precious research resources are to be used intelligently. The temptation to work on a problem because it yields a more tractable mathematical model or is academically interesting must be seriously weighed against the gains to be expected. Quite often a less elegant attack on a more abstruse problem will show a greater return in terms of advancement of the state-of-the-art of structural design. Most agencies charged with expenditure of the structural research dollars are forced into continuing reappraisal of the emphases and aims of contract-supported shell instability investigations in the light of the near and far term mission requirements. The point of philosophy we wish to reiterate is that things now appear out of balance. Perhaps some of the research dollars now spent on shell instability might be given up and spent in more lucrative endeavors.

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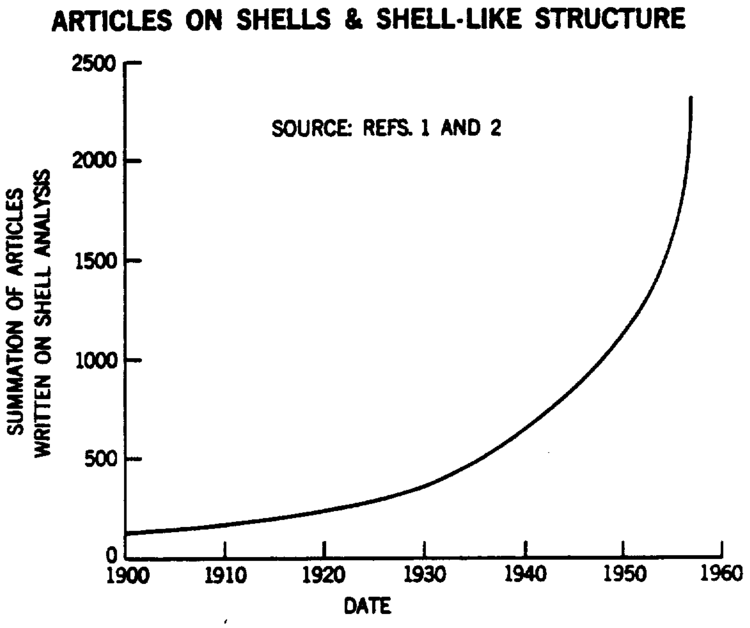

Figure 1

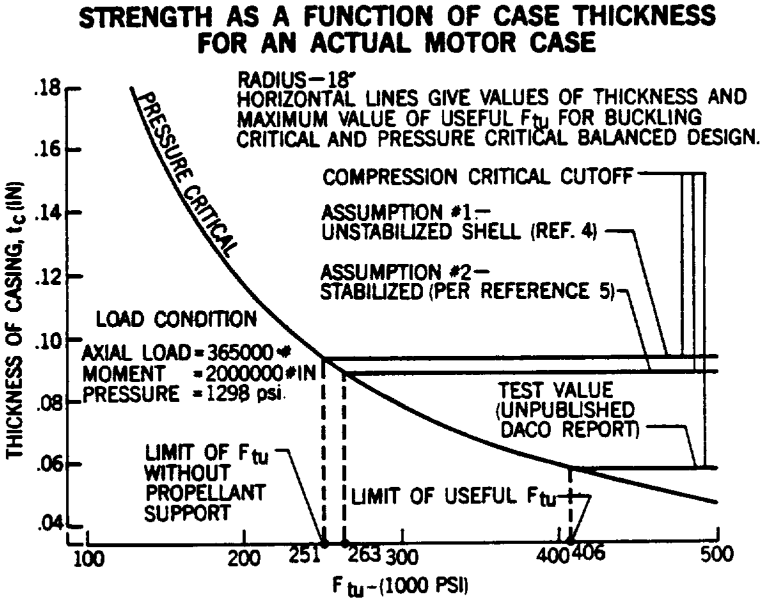

Figure 2

SEGMENT OF AN INTEGRALLY STIFFENED SHELL

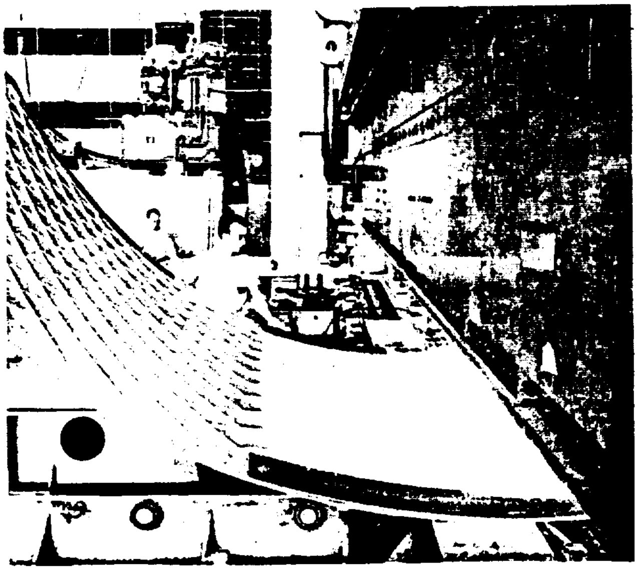

Figure 3

COMPARISON OF MINIMUM WEIGHT DESIGNS FOR VARIOUS STRUCTURAL SYSTEMS AND MATERIALS IN AN AXIALLY LOADED CYLINDER

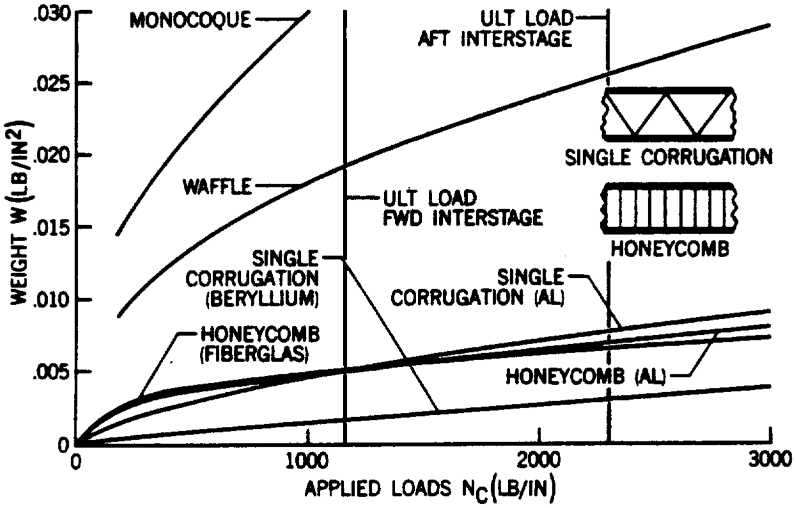

Figure 4

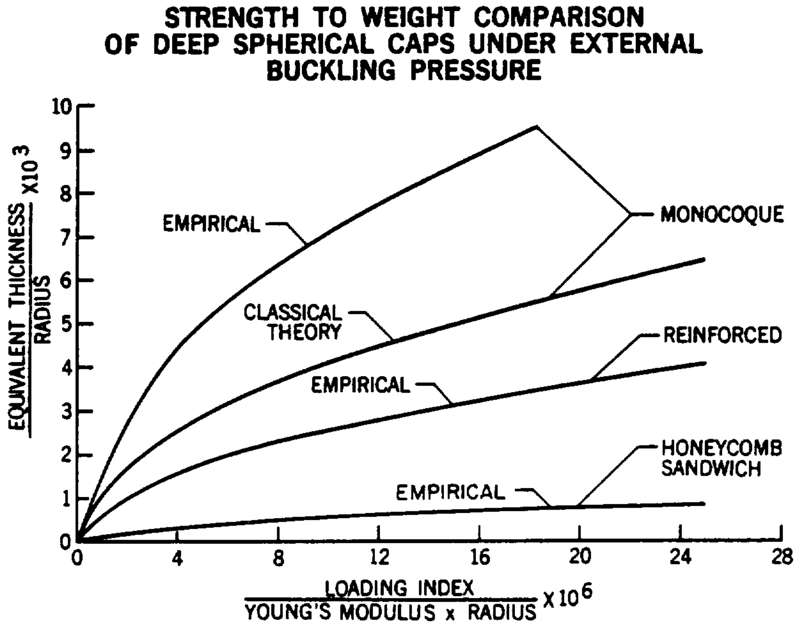

Figure 5

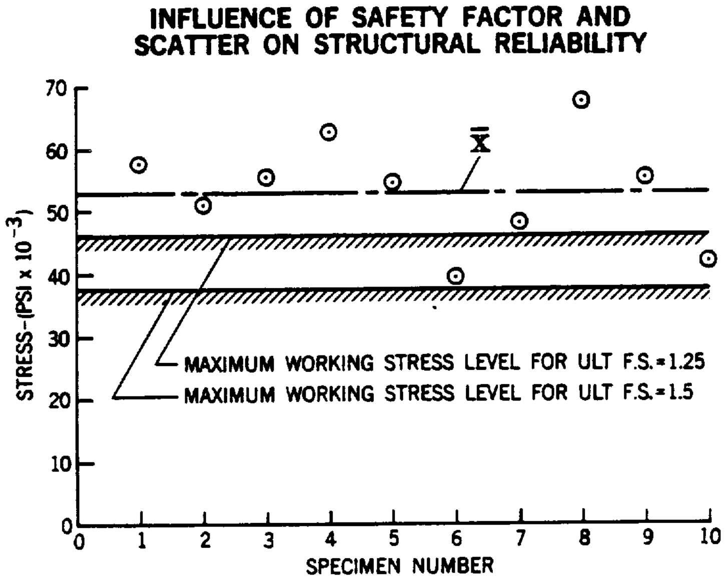

Figure 6