DESIGN OF STIFFENED CYLINDERS IN AXIAL COMPRESSION

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SUMMARY

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The problem of optimum design of axially compressed cylinders stiffened by rings and stringers is discussed. Particular attention is devoted to configurations suitable for large launch vehicles. Consideration is given to the analytical techniques for determining strength as well as the procedures for optimization.

INTRODUCTION

One of the primary design criteria for circular cylindrical shells in flight vehicles is the necessity of carrying axial compressive loading. In most situations, the loading is light enough so that efficient design precludes the use of an unstabilized, single-thickness shell. Of the various means of stabilization, the one used most often is that of stringer and ring reinforcement.

The purpose of this paper is to discuss methods of analysis and of optimum design of stiffened cylinders. Attention is devoted primarily to types of configurations and loadings which are suitable for large-scale launch vehicles. Only the case in which integral stringers are firmly fixed to the rings and in which premature local buckling of the skin between stiffeners is prohibited is considered, in the belief that these are inherent properties of the most efficient structure. For simplicity, the stiffening elements are assumed to have negligible torsional or sidewise bending stiffness.

Most of the information contained herein is not particularly new or surprising. It is felt, however, that the discussion taken as a whole is a contribution to the field of optimum design.

DISCUSSION

Before looking at the complex stiffened cylinder, there are some lessons to be learned from published analyses of the much simpler stiffened flat plate. For example, a study of the results of reference 1 shows that a longitudinally compressed, longitudinally stiffened rectangular plate with many bays in the transverse direction, buckles as if the bending stiffness of the stiffeners was "smeared out", provided that the stiffeners are not so stiff that local buckling of the plate between stiffeners occurs. For the present case wherein premature skin buckling is prohibited, this means that the stringer stiffening can be very adequately accounted for by means of orthotropic analyses. Since the larger the stringer, the larger the ratio of stiffness to weight, it also means that a necessary condition for optimum design is that local skin buckling, stringer crippling, and overall cylinder buckling should occur at the same load level. In short, for a given required distributed stringer stiffness determined by orthotropic theory, optimum design implies that the stringer spacing be as wide as possible without encountering local skin buckling, and as deep as possible without creating crippling.

The situation with regard to rings is unfortunately not so straightforward. Qualitative help is afforded by the results in reference 2 for the longitudinal loading of transversely stiffened long plates. These results have been replotted in figure 1 in a form suitable for the present discussion. In this form, the buckling curves that occur if the stiffener were stiff enough to force local panel buckling and the curves predicted by an orthotropic analysis are the same for all proportions; these are shown by the dashed straight lines. The exact results for the discrete stiffeners are indicated by the solid curves. These curves are very nearly coincident for practical panel aspect ratios. There are three ranges of the stiffness parameter: For light stiffeners, the curves follow the orthotropic theory; for heavy stiffeners, the panel is forced to buckle between stiffeners. In the intermediate range, the stiffeners participate in the buckling and their discreteness is important.

Several lessons pertaining to the buckling of stiffened cylinders are learned in this figure. For example, there is no need of making the rings stiffer than a certain value. Furthermore, since the larger a ring is the more efficient from a weight standpoint it is, the range in which the orthotropic ring theory is valid should be avoided. The optimum design will have a ring stiffness that would be associated with the intermediate range. This is unfortunate since in this range analysis techniques are the most difficult. In addition, the optimization procedure would have to include the complicated coupling between the stringer stiffened cylinder and the rings. Without very much cost in weight one can eliminate part of this coupling by adopting the criterion that the rings should be made just stiff enough to force nodes at the rings.

On the basis of this criterion one can design the optimum stringer panels for buckling between rings; this would depend only on the loading and the ring spacing. Then the rings can be sized so that the selected buckling mode would be obtained. A subsequent optimization with respect to ring spacing would yield the final efficient design.

The carrying out of the foregoing optimization procedure is feasible within the present state of the art of analysis techniques. A discussion of some of the interesting aspects of this state of the art follows:

Analysis of Stringer Stiffened Cylinders

If one can ignore the effect of "one sidedness" of the stringers, there are a number of orthotropic cylinder analyses that are applicable to solving this problem. Such an analysis should include the effects of plasticity since optimum design should entail sizable stresses. This is particularly true if the cylinder is pressurized. The inclusion of these plasticity effects for the pressurized case can be a source of trouble because of the difference in effective stress levels between shell and stringers. Analysis shows that the shell becomes plastic at a considerably lower load than do the stringers.

Theoretical results obtained from such orthotropic analysis should be in good agreement with the strength that would be realized experimentally even though small deflection theory is utilized. This conclusion follows from an examination of the kinds of configurations that are optimum for large launch vehicle structures. Here the optimum ring spacing turns out to be relatively small and most of the load carrying ability of the stringer stiffened cylinder is contributed by its wide column capability. The contribution of the curvature, which is most subject to reduction due to large deflection effects, is relatively small. Furthermore, a stringer stiffened cylinder turns out to have a relatively low effective radius-thickness ratio so that the knockdown in cylinder strength is small. These conclusions are based in part on the results obtained in reference 3 by means of an approximation of the orthotropic analysis of reference 4.

An investigation of the influence of the one sidedness of the stringer stiffeners in practical cylinder design is being performed by the author. Preliminary results of the investigation indicate that for the axisymmetric mode of buckling, locating the stringers on the inside yields a significantly higher strength than locating them on the outside. For most asymmetric modes of buckling, the converse is true. Since the critical mode of failure is usually the latter, attention should be given to the possibility of utilizing external stiffeners in design.

Determination of Required Ring Stiffness

As was mentioned before, efficient stiffened cylinder proportions require the rings to be handled as discrete entities rather than by means of orthotropic techniques. An oft used practice is to size the rings in accordance with Shanley's criterion, reference 5, which is a conservative quasiempirical specification based on the envelope of a large number of test data. For large launch vehicles, Shanley's criterion yields rings that contribute significantly to the overall weight of the cylinder. A more refined technique, based on the detailed geometry of the cylinder and its stiffeners and treating the rings as discrete elements, is therefore an important adjunct to efficient design.

Examination of various proposed designs for launch vehicles in the Nova class shows that the tank domes and the manufacturing splices divide the structure into relatively short cylinders. For such configurations only a few additional rings are necessary in each segment. Therefore, analyses of "infinitely long" geometries are of limited usefulness. One must deal with the actual structure, incorporating the restraint effects of domes and other attachments in order to get accurate strength estimates. Mathematically there are two ways of dealing with each of the cylindrical segments. One is by writing the 8th order partial differential equation for the stringer stiffened cylinder with the proper boundary and discontinuity conditions at the ends and across rings. The other would be to use a potential energy approach. In either case, various values of circumferential wave length would have to be examined and the rings sized in order to yield at least as much strength as that already determined for the stringer stiffened cylinder. Of the two approaches, the energy approach would seem to be more suitable for programming on a computer.

Effects of Alternative Design Conditions

As is usual in structural design, launch vehicles are subjected to a variety of loading conditions. The tank barrels, for instance, must be capable of withstanding not only the very large flight compression loads coming from the combined longitudinal acceleration and wind shears but also less large, but still appreciable, compression loads on the launch pad. The high reliability requirement for man rating dictates capability of any tank's being empty and unpressurized while all upper stages are completely fueled. The necessity of meeting both of these design loadings well may yield a tank structure which is optimum for neither of the loadings since the pressurization existing during flight reduces the requirements for rings but increases the plasticity problems. The first rough cut would be gotten by designing the tank barrels without rings for the flight condition and then adding a sufficient number of rings to handle the launch pad condition. Further refinement is necessary, however, for weight saving.

CONCLUDING REMARKS

All actual designs are affected by the practical aspects of fabricability; off-optimum design therefore usually results. Nevertheless, the optimum configuration should be determined, if for no other reasons than to determine what the cost of such practical considerations is, and to indicate the direction in which improvements in manufacturing technology would be most helpful. In addition, for very large launch vehicles, optimum configurations might well be feasible because of the absence of minimum-gage problems.

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LONGITUDINAL BUCKLING OF TRANSVERSELY STIFFENED PLATES

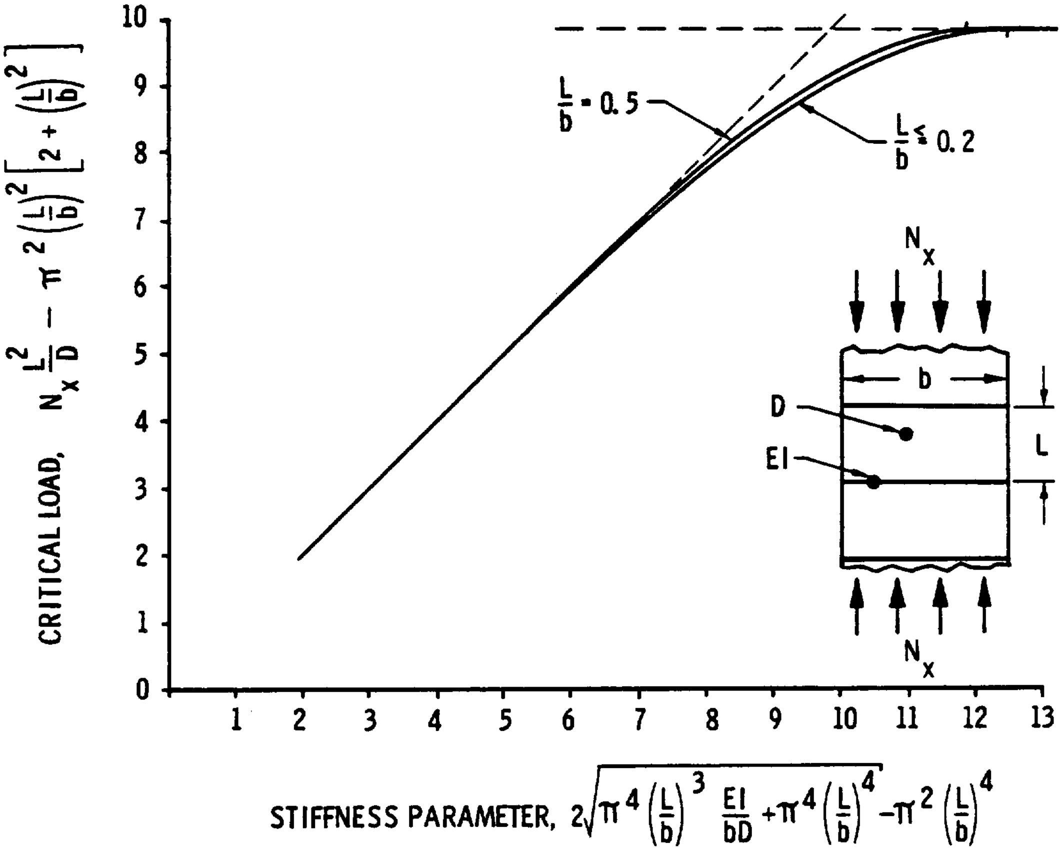

Figure 1