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SPACE RESEARCH SPINOFF TO STRUCTURAL ENGINEERING

by
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Summary

Research for space applications has resulted in a considerable amount of valuable spinoff information to practicing structural engineers outside the space related fields. The spinoff has not been limited to any one field, but cuts across the lines of many industries serving the public, For example, specific applications can be traced to the agricultural industry, commercial power generation, school and building construction, and hydrospace applications.

Examples are given where funds from NASA and other space oriented organizations have been combined with funds from private organizations such as the American Iron and Steel Institute, the American Institute of Steel Construction and from private corporations to produce results that are applicable to both space efforts and commercially oriented efforts.

Several projects such as shell structural research and the effects of sonic booms on older structures are suggested that would accelerate the spinoff.

It is suggested that a significant portion of future structural research should be integrated and should apply to the general field. This would avoid duplication of effort that has often occurred in the past and release prime investigators for advancing the state of the art of structural design.

Introduction

Structural Engineering, like most other professions, has changed significantly in recent years. Twenty years ago the college trained engineer was given extensive training in either of two areas. He was either trained extensively in structural analysis of beam and column type structures using the methods of moment distribution, slope deflection and their variations or he was trained extensively in plate and shell type structures using the methods presented by Timoshenko and others. Today the structural engineer that is prepared in only one area is at a distinct disadvantage. The educational institution that gives a student only one type of training is shortchanging him.

Not only has the type of structures outside of the aero-space industry changed to include both beam-column-type structures and plate-shell-type structures, but the development of the computer has allowed the structural engineer to analyze the modern structure in a fraction of the time formerly required. A number of years ago an engineer would have to spend months on the analysis of a multi-story building. Today a single computer analysis can be completed in less than a day. As a result, the structural engineer now has time to think more about the type of structure to be used and can more nearly develop the optimum-minimum-cost design.

Twenty years ago the thin shell type structure was almost limited to the aircraft and missile type structure. This is not true today. Some of the thinnest shell type structures are now used outside of the aerospace company products.

The professional structural engineer is now called upon to engineer structures in industries far removed from the old building-bridge type structure.

Agriculture Industry

The changes in Agriculture have paralleled those in other fields. Today the farm is becoming more and more industrialized. Cattle feeding is a good example of how the nature of the business has changed. The old days of the cattle grazing on large plots of land have given way in many locations to industrialized production and feeding. Today one can see confined areas where thousands of cattle are fed and live in a semi-automated relatively small area.

The center of the area usually contains several forage tanks, see Figure 1. These feed tanks are air tight and are automatically loaded and unloaded. A typical tank might be made of 1/8 in. thick, specially treated steel and be about 25 ft. in diameter. This radius to thickness ratio of the order of 2,000 to 3,000 compares to the radius to thickness ratio of aircraft components, space boosters, etc. The tank is unloaded by a horizontal screw auger which rotates 360° about the center of the base of the tank.

The structural design of the tank involves many of the methods that are used in designing aero-space structures. The weight of the forage causes circumferential tension in the tank. As the forage is unloaded there is friction between the forage and the walls of the tank that causes axial compression. Thus the basic design must account for both the circumferential tension and axial compression and is essentially a stability type of design. The methods outlined in

NACA, TM 2021[1] are often used to calculate the critical loads. The safety factor is often of the order of 1.05 to 1.10 and is thus comparable to the aero-space type of structure.

The structural designer must take into account the production and erection methods to arrive at an economical design. If tolerances were specified that are comparable to aero-space structures, the cost of the tanks would be so high that the resulting design would be purely an academic one. As a result, the structural designer must make a careful analysis of structural stability based upon deflection caused by edge conditions, initial imperfections, etc. The methods summarized in NACA TN 3783[2] and the methods suggested by Hoff, Batdorf, Stein, and many others must be used. Quite often stiffeners are used on the lower part of the tank to increase the buckling resistance of the shell.

It is estimated that the market potential over the next several years for this type of tank is of the order of 100 million dollars. Thus, future research projects on the effects of edge conditions, imperfections, stiffened shells and psuedo-elastic effects are needed and would result in significant cost savings to the industry.

It is interesting to note how value engineering has been applied to these designs. Several years ago conventional methods were used to build the foundation and the tank. Normally about a month was required to erect a tank. After a concentrated effort on cost reduction, a method was developed for integral foundation and tank design and the tank was erected by building the structure from top to bottom. A special erection device was designed whereby the top and upper portion of the tank were built first and then jacked into position. As a result, the construction time was reduced from about a month to five days.

A rather dramatic new change is developing in cattle feeding as a result of recent research. It has been found that significant cost savings will result if the cattle are housed in a heated area in the winter and air conditioned area in the summer. Designs are now being prepared that will be integrated systems involving the environmental design as well as automatic feeding, waste removal and automatic waste treatment etc. One firm is designing such a system to house about 15,000 cattle. Preliminary studies have indicated that shell and dome like structures might be the most economical type that can be used. The results of space research have aided significantly in the design of these structures.

Building Industry

Perhaps the most significant new use of very thin shell techniques in structural engineering is the development of the dome type structure. Figure 2 shows one of these developments. The so-called reticulated shell is made of thin steel tubing that for all practical purposes behaves as a shell. The equivalent membrane thickness is about 0.030". With a radius of 80 ft., the radius to thickness ratio is about 30,000 which even by aero-space standards is a very thin shell. Many shells of this type of design have been built as framed domes (made with structural steel members) or stiffened shells (made of a thin metal shell with stiffeners, See Figure 3). The Houston Dome (640 diameter - See Figure 4) is another example of this type of structure. Domes with 1000 ft. base diameters are now in the final design stages. A preliminary design of a mile base diameter dome has been made.[3] Preliminary planning is under way for a medium size city under a 2 mile diameter dome.

All of these structures may be classified as doubly-curved orthotropic shells. All have details that give the shell-like structure a high bending stiffness to resist buckling. A great deal of research has been done within the aero-space field on this type of structure.[4,5,6,7,8,9,17,19,22,23,26,28] Perhaps even more research has been done outside the aerospace field,[10-32]. It is interesting to note that the research on aerospace structures applies to this type of structure as well as the research on buildings in general, underwater structures, military structures, and chemical and petroleum industry structures.

As one looks at the problem in general, one cannot help but notice a significant amount of duplication of effort in the various fields. For example, a number of researchers have spent significant amounts of money on experimental programs attempting to get reliable repeatable results on spherical caps. A thorough literature search would reveal that reliability has already been obtained and actually a commercial product is already available where the product will give repeatable results in the laboratory to ±2% and in the field to ±5%,[17,29](See Figure 5). The commercial product has been developed based upon more than 1,000 tests on many types of materials and sizes. One very important parameter in developing reliability is the so-called pseudo-elastic effect. This effect can be traced to the large deflection effects on shell buckling and accounts for the fact that even though the shell is thin and the membrane stress just prior to buckling is only a fraction of the yield strength of the material, the buckling process is an elasto-plastic one. This effect has been demonstrated both experimentally and theoretically.[17,22,23]

The designer of a dome must adjust theoretical results to take into account construction tolerances, edge effects, and pseudo-elastic effects. The split rigidity concepts used years ago in aircraft research on plates has been extended by the writer to orthotropic shell stability problems.[16,28] The effects of deflections etc. on the stability of orthotropic shells have been analyzed theoretically,[28] and the results for unstiffened shells compare very well with the results of controlled tests made at the Navy-David Taylor Model Basin.[13] The edge effects have also been studied[28] and the theoretical results compare favorably with the recently published results in the AIAA Journal[9] for unstiffened shells.

The University of Missouri results were obtained with the financial assistance of NASA as well as the AISI and AISC. Some six private firms also contributed to the projects.[17] It is interesting to note that the general approach used applies equally to aerospace as well as other structures.

The reticulated dome in Figure 2 illustrates a case where value engineering was applied to the engineering design itself as well as to the fabrication and erection. In the initial design phases of the development the computer was used. Each analysis often cost several thousand dollars which in some cases made the roof non-competitive. A study of the basic differential equations of the system under symmetrical loading revealed that the split rigidity concept could be used and the engineering could be done for less than 1/10 of the computer cost. Next new computer techniques were developed (as well as competitive suppliers of time and program) and the original computer costs were cut by an order of magnitude. Research programs are now underway to develop closed form solutions for unsymmetrical loading. It is estimated that in the near future an engineer will be able to analyze this type of roof in several hours. He can then focus his attention on alternate and optimum designs.

One of the high cost items in the original plans of this type of roof was the high erection labor cost. Several years ago it was proposed[3] that roof of this type could be erected by cantilever method with no falsework or shoring. This was difficult to sell because it is always difficult for engineers and erectors to think in three dimensions. Last year this type of erection method was tried and successfully completed - See Figure 6. The result - 5 days erection time with a 4 man crew for a 100 ft. diameter roof.

Commercial Nuclear Power

Most of the new commercial power plants under design in the U.S. today are nuclear. As a result, structural engineers are facing new designs that are unprecedented. Here again space research spinoff has been a valuable asset to the design process. One example is the design of containment vessels. A typical vessel is cylindrical with a spherical head and is about 100 ft. in diameter and 200 ft. high. A steel linear plate is used that is about 1/4 in. thick and the main shell is often post-tensioned concrete of the order of 3 ft. thick. The steel shell is anchored to the concrete at intervals with channels or with studs.

One of the most critical design conditions is the accident analysis. In this case the steel shell temperature could exceed 300°F, and the average concrete shell temperature is much lower. As a result the steel shell is prevented from expanding and is subjected to very high compressive stresses. The structural engineer must determine if the shell buckles (in most instances it will) and if it does, what loads are put on the connections between the steel and concrete. In order to evaluate this condition, the engineer must know the post-buckling deformation and strain pattern in the shell. Recent developments in shell theory often developed in the space program are used in this case. However, the designer soon finds himself in unchartered territory because very little research has been done on post-buckling geometry. Here again, the pseudo-elastic effects often predominate.

Underwater Structures

Underwater structures are in a rapid state of development by the Navy and by some commercial firms. Offshore drilling rigs and their related structural problems are a challenge to the structural engineer. New shapes of structures have been investigated to meet the new challenges.

In many cases, the controlling condition is the stability of the structure. The references in the bibliography are often used to assist the researcher designer. Here again one notices the great amount of overlap in the research efforts.

Sonic Boom

In the next few years the aerospace scientists and engineers will find themselves in a new position relative to the general public. They will find themselves directly associated with public safety both in the home and in public and private buildings. The sonic boom causes deformation and loads on structures that were not contemplated when the structures were built.

As engineers personally observe older buildings under the action of sonic booms they must conclude that considerable, immediate research and observation must be done on the magnitude of the loads, the magnitude-time history of the loads, the damping in older types of structures, the fatigue strength of various types of buildings, etc. Is the house with plastered walls obsolete? Is it safe under repeated sonic booms? Many buildings in downtown areas are marginal from a public safety standpoint at the present time. Will sonic booms cause public safety hazards?

Future

All indications lead to the conclusion that present trends in structural engineering will continue and probably accelerate. If so, the present research methods need to be examined in detail. It appears that structures in general should be researched. With little effort the engineer doing research for the space program can make his results applicable to other fields as well. The few programs referred to herein attest to the fact that this could be done.

It might be well to pause and note the basic difference in the development of aerospace structures from those in the private sector. The aerospace structure development often follows the scientific method. That is, the idea is first, research second, development third, design and production last. The building structure development has often followed almost the reverse order. That is, the idea first, the building second, the design and development to refine the product third, and then finally the research to further develop the product. Recent trends have tended to change this order, but the trend is by no means universal.

The aerospace community has an excellent opportunity to contribute to structural upgrading. It has the qualified people and above all it has the excellent structural laboratories with equipment and facilities that are beyond the University researchers' and private structural engineers' dream.

The following paragraphs give only a meager sample of the type of research that could cause a multifold increase in the spinoff from space research to structural engineering.

The previous examples showed how shell structures are being used at an increasing rate in non-aerospace fields. Similar examples could be given for plate structures. The biggest single problem in shell structures is stability. Ever since 1915 when Zoelly presented his theory on shell stability, researchers have been seeking the secret of the physics of the problem. Even today in spite of some 3000 plus papers per year on shell structures the physics of the problem eludes the researcher. Perhaps the recent paper by Army researcher, Adachi,[15] gives a clue to the nature of the problem. Adachi showed that the buckling process occurred in a fraction of a milli-second. Why not combine the efforts of the wind tunnel instrumentation engineer who is used to measuring quantities in short time periods with the efforts of the structural engineer to tie down the physics of the buckling problem? When the physics is known, the more accurate mathematical model should be forthcoming.

The aerospace laboratory appears to be an excellent place (where considerable equipment and instrumentation is available) to separate the variables of the problem. One cannot really expect to include the effects of imperfections, bending stiffness, pseudo-elastic effects, edge effects and fabrication residual stresses in one series of tests and then hope to separate them in the analysis. A comprehensive series of tests which separate the variables appears to need to be done. This type of program cannot be done with a few thousand dollars in a few months in a small University laboratory.

The structural engineer desperately needs some large scale tests. Here again the aerospace laboratory could be used. The large environmental chambers could be used with large scale experimental heads to test effects of residual stresses, etc., on the stability of large roofs. Actually these large tests would still be relatively small scale models of actual structures.

Perhaps the greatest need of all could be supplied by the space research field. There is a need for a place where structural research is cataloged. The spinoff could be in both directions. Certainly the space researcher needs to be familiar with shell research to design such structures as the common bulkhead in a space booster. In order to do his job well, he needs to not only be familiar with the work in the aerospace field, but also needs to see what has been done by searching such publications as the Journal of the American Institute for Steel Construction, the reports of the American Iron and Steel Institute, The Journal of the International Association for Shell Structures, the publications of the International Association for Bridge and Structural Engineers, Acta Technica of the Academial Scientiarum, Hungary, Der Stahlbau, Architectural Design, London, the Proceedings of the American Society of

Civil Engineers, Chemical Engineering, David Taylor Model Basin Reports, Reports of University Experiment Stations, International Conferences on Space Structures, etc., etc., etc. The time has long since passed when one person can keep up with one part of one field such as shell stability.

NASA could perform a great service both to the aerospace field as well as to the structural engineer by expanding the publication, Scientific and Technical Aerospace Reports to include the majority of research work applicable to plate and shell structural engineering.

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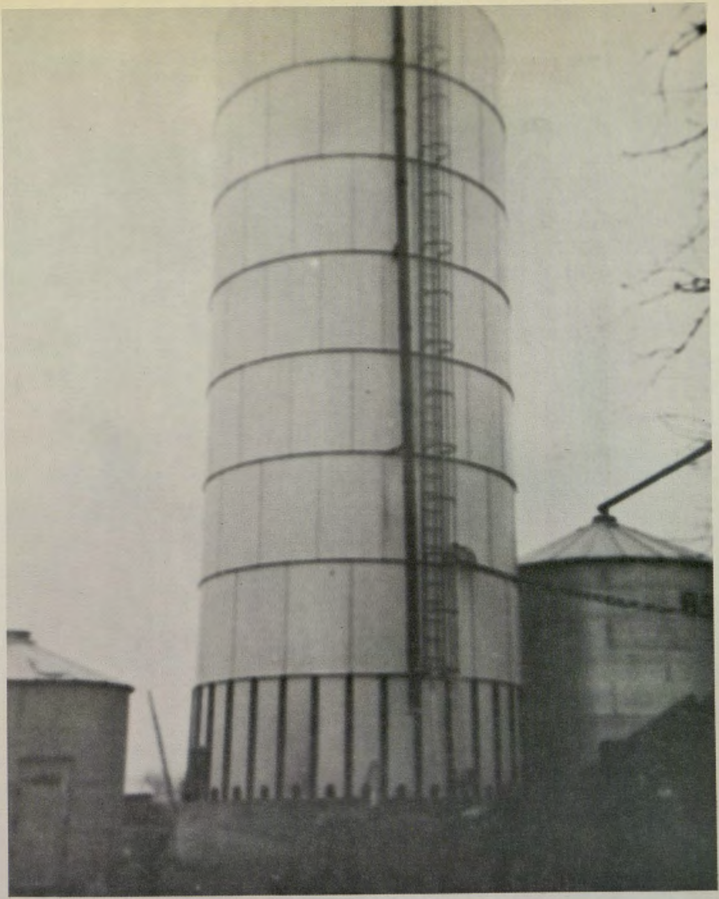

Figure 1 - Typical Forage Tank (Courtesy of Black Sivalls & Bryson, Inc.

Figure 2 - Reticulated Roof (Courtesy of Butler Manufacturing Company).

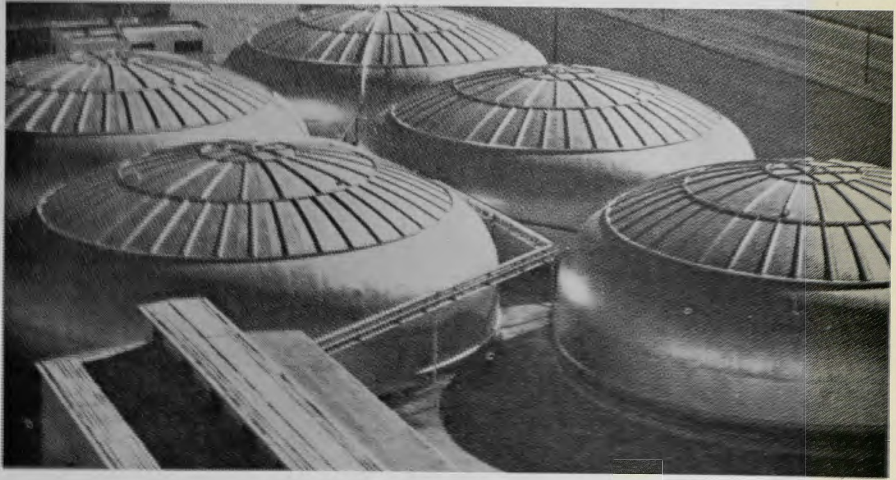

Figure 3 - Stiffened Shell (Courtesy of Chicago Bridge and Iron Company).

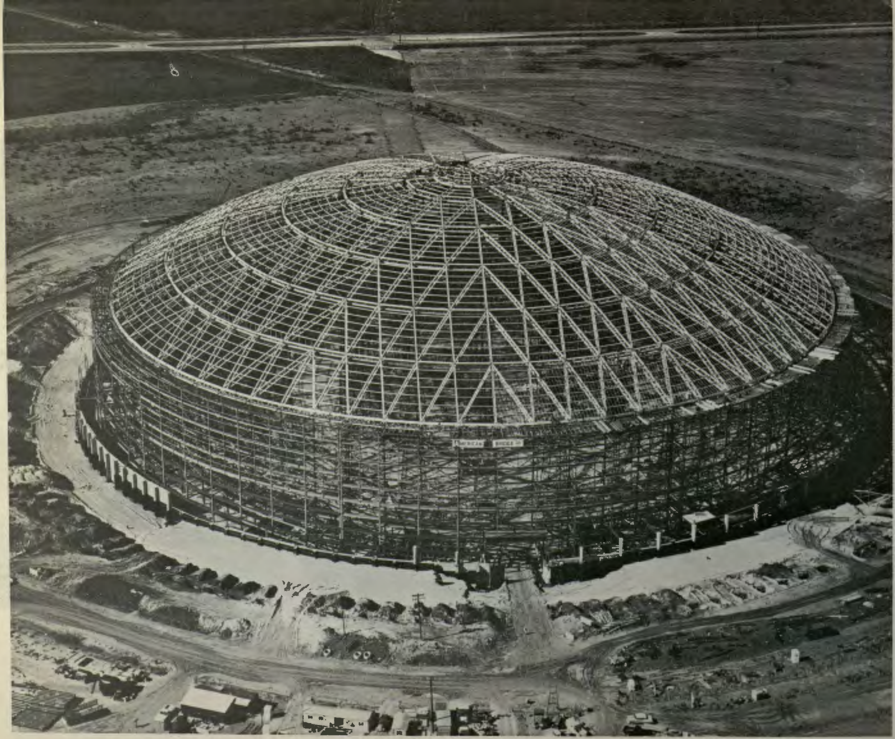

Figure 4 - Houston Dome (Courtesy of U.S. Steel Corp.).

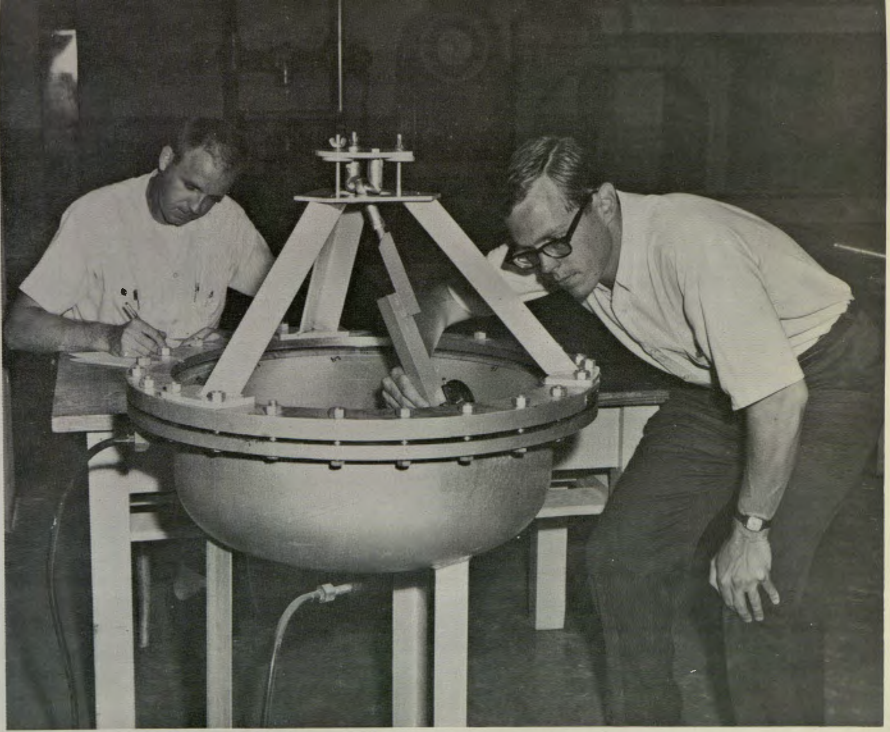

Figure 5 - Laboratory Test on Spherical Cap at University of Missouri Shell Structures Laboratory

Figure 6 - Cantilever Erection Method on Dome Roof.