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SHELLS AS LOAD MEASURING DEVICES: A UNIFIED STUDY TO MAXIMIZE ELASTIC LOAD CAPACITY

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Abstract: Shells have been the subject of several types of structural investigations in the past due to their attractive property of high load to weight ratio. The broad aim of this study is to study suitability of shells as load measuring devices. This paper discusses a shell device for measuring loads and provides a framework for design studies to maximize load capacity. To accomplish this, we propose a unification of design space and perform a consolidated design of experiments to quantify the relative merits of configurations. The design framework includes both geometrical and material properties to enable generic conclusions and extensibility. A validated finite element model has been used to aid in detailed structural assessment. A significant increase in load capacity has been obtained compared to previously reported configurations paving the way for compact device setup.
Keywords: Shells, Elastic limit, Finite Element Analysis, Transducer

Nomenclature

R	Outer Radius of hemispherical shell
r	Inner radius of hemispherical shell
t	Thickness of hemispherical shell
h	Height of hemispherical shell (r+t)
r*	Radius of flat portion
E	Young's Modulus
Y	Yield strength
t/R	thickness ratio

I. INTRODUCTION

Shells subjected to compression by a rigid flat plate has been extensively studied in the literature both experimentally and numerically. These studies focused on elastic, elastic-plastic and buckling characteristics of conventional hemispherical shells. A brief overview of key literature is presented below along with motivation for the present study. Reissner[1] investigated the shell-plate contact problem and provide expressions for direct and bending stresses for shallow shells with $h/R < 4$. Naghdi[2] later extended Reissner's study to include the effect of shear strains. Kalnins[3] devised a multi-segment method for nonlinear analysis of elastic shells. Updike etal[4] investigated the load behavior of an compressed elastic shell, coming up with an analytical formulation for elastic load-deflection and also buckling phenomena wherein the shell deforms with an axisymmetric dimple at the center. Subsequent studies by Shwarz[5] and Kitching[6] focused on load-interference behavior as a function of shell thickness and radius. Interestingly, they were looking at contrasting shell applications, one concerning cornea and other collision of vehicles.

Gupta etal[7] focused on buckling of hemispherical shells across a range of thickness ratios and showed good agreement between experimental and theoretical results. Another interesting shell load application to ping pong ball was studied by Pauchard etal[8]. Shariati etal[9] performed experimental and numerical study of buckling behavior of steel shells with flat tops under various loadings.

Some of the theoretical investigations were limited to elastic deformations while continuous increase in load initiates plastic deformation occurs before initiation of buckling. If a shell is to be used as a load device, it is important to avoid initiation of plastic yielding. For a given material, this elastic limit is fixed and geometry gives additional degree of freedom to extend the design space. Understanding the physics of plastic yielding viz dependence on geometrical/material properties and its initiation location helps in effecting design changes to maximize load capacity (i.e. high elastic capacity with a compact design). To enable larger exploration of the design space, study the stress fields and quantify the increase in load capacity, we use a validated finite element model. The study of Longqiu Li etal[10] provides a pointer in using FE model to derive useful information on onset of plastic yielding but is limited to the treatment of spherical shells. The motivation for current study is derived from novel application of shells as load measuring devices, covering both static and dynamic loads. Next section shows more details of such an application and possible use cases. To enable such successful application and demonstrate high performance, it is imperative for the shell to be as compact as possible while maximizing the load bearing capacity without yielding. As stated, shell design space is expanded to achieve this goal within elastic limit.

1. Case Setup
2.1 Load Device

The build-up of the shell load device is shown in Fig.1 and description is as follows. Multiple shell elements are placed between two rigid plates which form the outer covering of the device. Any load onto the rigid plates is transferred uniformly to all the shells which in turn undergo deformation. The piezoelectric transducer placed between the rigid plates serves to measure this deflection by a change in voltage which is calibrated to the load acting on the device. Piezoelectric transducers are placed at multiple locations to mitigate sensitivity to placement. As mentioned before, maximizing the load capacity of a single shell will reduce the footprint of the device by reducing count, height of shells and hence weight of the device.

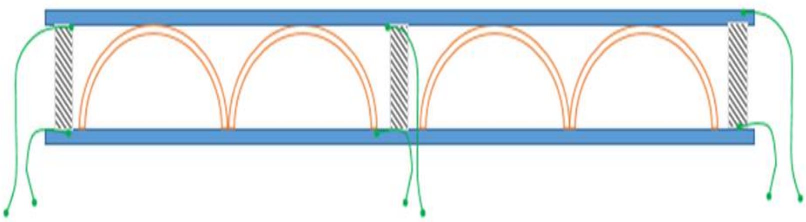

Fig 1: Shell Load Device

2.2 Design Study DoE

Conventional design parameters of shells studied in the literature include thickness (t), outer radius (R) and material properties such as Young's Modulus (E) and Yield strength (Y). In Ref [10], it has been shown that the load capacity of conventional hemispherical shells can be related to a non-dimensional parameter λ, (Eq-1). It is reported that, for hemispherical shells, critical load attains a peak of 4times that of solid sphere at
λ =0.75.

$$\lambda = \log\left(\left(\frac{t}{R}\right)\left(\frac{E}{Y}\right)^{0.886}\right) \quad ....Eq. (1)$$

The current study aims to answer the following open questions:
1) Can create a unified design study to extend the shell design space?
2) Can such a design space help in further increase of load capacity? If yes, in what way and by how much?
3) Can the shell be made more compact without losing the increased load capacity?

To facilitate, the following parameters have been introduced to expand the design space.

- **Radius of flat portion on top of the shell (r*):** Intuitively speaking, the contact region of the shell will have a bearing on the stress distribution and hence elastic limit. However, the improvement in load capacity and interaction with other variables is to be determined.
- **Height of the shell (h):** Ability to adjust height can potentially help to make the shell more compact. However, it is to be seen if this has any adverse impact on load capacity.

Making these parameters non-dimensional with respect to the outer shell radius, we now have the following additional parameters.

a) Flat-top Radius Ratio (r*/R)
b) Height ratio (h/R)

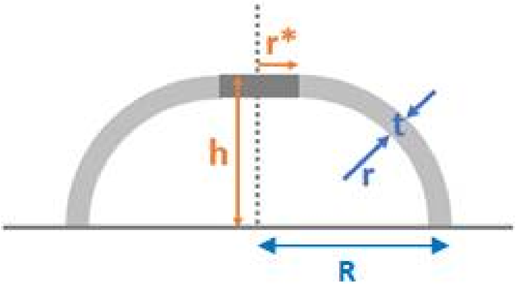

Fig 2. Shell parameters

Fig.2 shows the consolidated design parameters (blue – conventional parameters & orange – additions) In addition to these geometry variables, material properties are also included in the design study. The DoE table with min/max limits of each variable is as shown below.

Variable	t/R	r*/R	h/R	E/Y
Min	0.02	0	0.25	100
Max	0.6	0.1	1	200

Before embarking on studying the impact of new design parameters, a validation study is carried out with conventional parameters. Results quoted in Ref [10] have been successfully reproduced with the finite element model. In this process, iterations were also performed on mesh density to ensure the adequacy of the model for further design studies. Details of the FE model are shown in the next section.

2.3 Finite Element Model

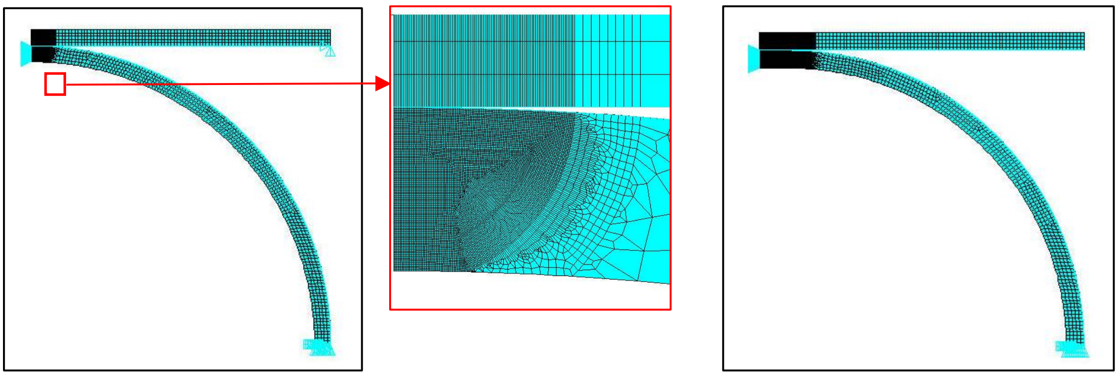

Fig. 1(a) FE model of hemispherical shell with zoomed view of the mesh near contact

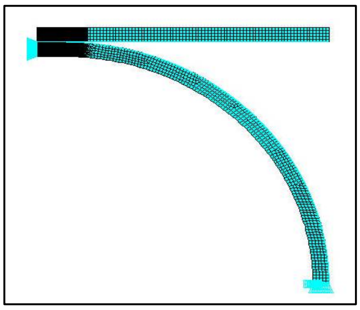

Fig 1(b) FE model of the shell with flat top

The FE model is an axisymmetric shell between top and bottom rigid plates. The shell is fixed to the bottom rigid plate and hence it is constrained in vertical and axial directions as shown in Fig 1(a). On the top side, contact is simulated between the shell and the rigid plate. Only one half of the axi-symmetrical hemispherical shell is modeled exploiting symmetry.

On the symmetry end, model is constrained in horizontal direction. The setup is shown in the Fig 2 along with several parameters that uniquely define a configuration. ANSYS axi-symmetric shell element PLANE183 is used to model shell & rigid plate. The top plate is made rigid by imposing young's modulus of 1000 times the shell material. Displacement is applied on the top rigid plate and is divided into 100 load steps for accurately capturing the non-linear contact and elastic-plastic transition. The typical mesh count of the model is ~35000 and it typically takes 0.5 hour to run on a 2-core 3GHz CPU. The zoomed portion of the mesh near the contact region is also shown in the adjacent figure. APDL macros have been generated to run through design studies in an automated fashion. This helps in performing multiple tradeoff studies using desired number of parameters and facilitates focusing on results.

2.4 Results and Discussion

A total of 125 simulations have been performed with various combination of design parameters. Results will be discussed in two aspects, first being the effect of flat top and second the height of the shell.

2.4.1 Impact of flat top radius

The hemispherical shell with flat top has been studied previously for buckling characteristics with various type of loading, but for elastic limit. Here we take a unified look at its impact on the crtical load as compared to hemispherical shell. Fig.3 shows the results of DoE with various flat top radii.

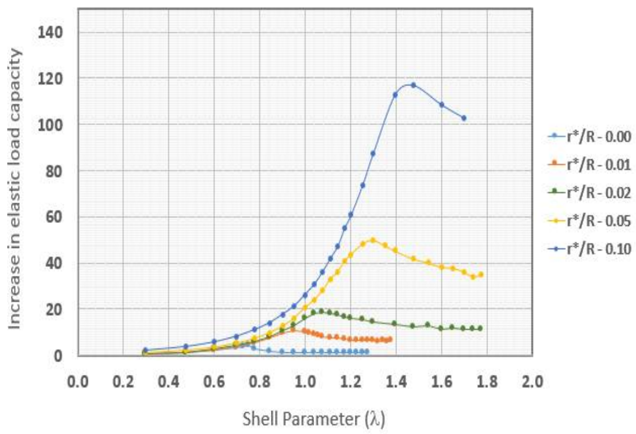

Fig 3. Impact of flat top radius on crticial load capacity

(Increase in elastic load capacity corresponds to the ratio of Elastic limits of hemispherical shells to that of solid sphere) The case of r*/R=0 corresponds to the previous study on hemispherical shells Ref[10]. Current model reproduces 4 times increase in critical load at ⍰=0.75.

Below are the few important characteristics of the shell response. Since the shell parameter has both material & geometric properties, it helps to see impact on geometry for a given material.

a) Introduction of flat top on hemispherical shell greatly helps in increased elastic limit, potentially influencing the stress redistribution near the contact point.
b) As the flat top radius increases, the peaking of critical load shifts to a higher thickness-ratio (for a given material), which points to higher weight of the device. This results in trade-off between load capacity and weight.
c) The trend of increased load capacity is relatively unchanged for lower thickness-ratios (< 0.8).
d) At higher thickness ratios, the load capacity reaches a new mean value (as opposed to 1 for hemispherical configuration)
e) The peaking of critical load becomes a more gradual transition with the addition of flat top.

We now look at Fig-4 how the deflections are affected by the addition of flat top. Deflection shows the following characteristics. Again here, the material properties are taken as constant to derive clear inferences on the impact of geometry change.

a) Deflection is greatly increased only for shells with lower thickness ratios (<0.8)
b) Smooth transition of peak critical load with the addition of flat top and its occurrence at larger thickness ratios can be clearly observed.
c) Interestingly, for shells with high thickness ratios, all curves appear to converge to same deflection

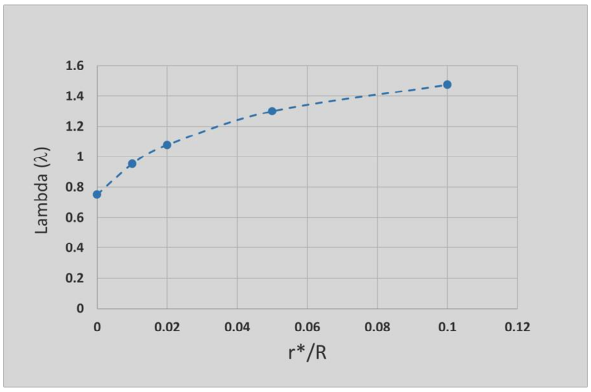

Fig 4. Impact of flat top radius on shell deflection

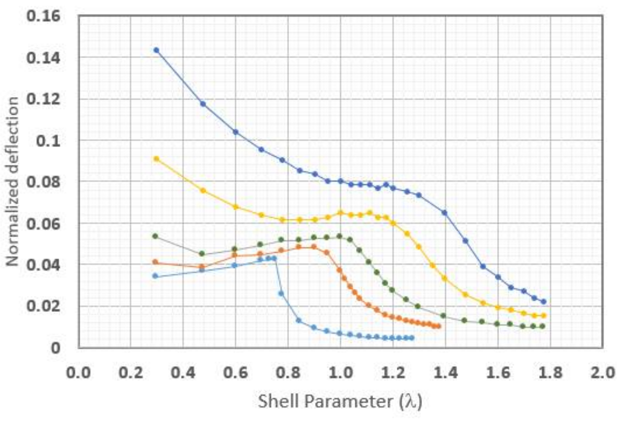

Fig.4.Impact of flat top radius on shell deflection

2.4.2 Impact of shell height

(Normalized deflection is the ratio of deflections of a hemispherical shell to that of a solid sphere) The above DoE is re-analyzed for a reduced height to assess its impact.

Fig 5 depicts a modified version of Fig 3 with the addition of load curve for reduced height (highlighted in red rectangle). It is seen that the global design change of height reduction has little or no impact on the elastic load capacity of the shell, thus providing an avenue for a compact design for applications where space is a major constraint.

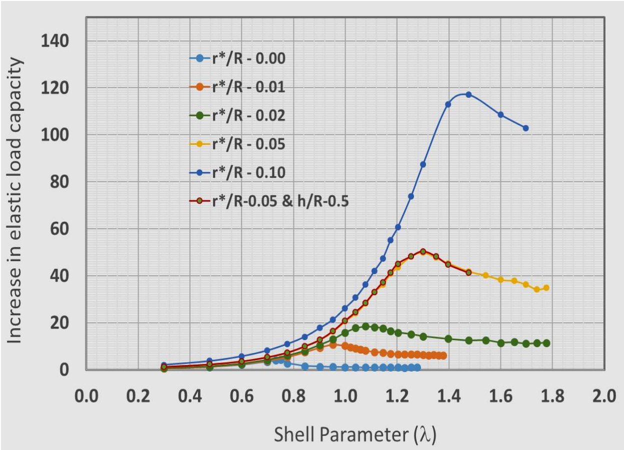

Fig 5. Comparison of load with baseline & 50% height

2.4.2 Generalized Shell Design Parameters

In summary, generalized shell parameters have been arrived at, leveraging the extended DoE in this current study.

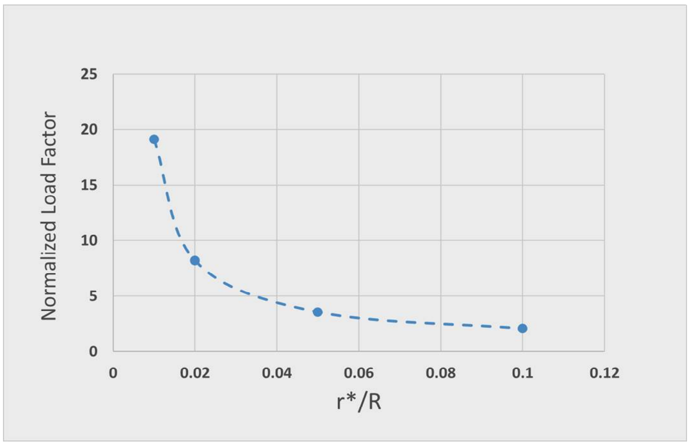

Fig 6. Influence of r*/R on critical lambda

The critical lambda (lambda at which the load attains peak capacity) increases with r*/R according to the following relation (as shown in Fig 6). This can be used to estimate the shell thickness for a particular choice of flat top radius and other design parameters.

$$\lambda - 0.75 = 0.4\sqrt{\frac{r^*}{R}}$$

A new parameter called "Normalized Load Factor" is defined and plotted as a function of flat top radius in Fig 7. It is defined as the peak load at a particular r*/R normalized to the simple compressive load required for the shell to yield for that r*/R. For r*/R of 0, the curve goes to infinity, due to infinitesimally small area of contact radius(r*→0). It is interesting to note that the peak load tends towards the simple compressive load as the flat top radius is increased.

2.5 CONCLUSIONS

This paper highlights novel application of shell as load measuring device and provides a framework for a unified design study to maximize the load bearing capacity of the shell. Effect of load capacity is quantified and contributions of newly added design variables has been shown to help in compact design of the shell while enhancing the elastic limit. As a continued study, experiments are planned with the shells to establish realization factor and study the fabrication and instrumentation aspect of the shells.

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