Nonlinear Finite Element Simulation of Large Deformation in Elastic Structure Shells under Localized Loading

AHMED ATTAA NEAMAH[1],
[1]Department of Mechanical Engineering, Islamic Azad university, Iran.

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ABSTRACT

This research work does a comprehensive nonlinear finite element simulation of thin elastic shells when subject to a localized loading and explains the role of geometric nonlinearity in large deformation. The researchers analyzed spherical and cylindrical shell models to investigate differences in stiffness, stress concentration, and post-buckling response. The model used the second Piola-Kirchhoff stress and Green-Lagrange strain tensor to account for large strain effects in an updated Lagrangian context. The results showed that the spherical shells exhibit sharp snap through instability, while the cylindrical shells behave with gradual reduction in stiffness with increasing indentation. Load-displacement and strain energy analyses clearly revealed the switch from bending-dominated deformation to membrane-dominated deformation. According to the study, linear theories will not be able to adequately predict the responses of shells to concentrated loads. Thus, nonlinear finite element analysis is necessary. This is essential for assessing the stability and performance of advanced structural applications.

Corresponding Author:

AHMED ATTAA NEAMAH
Department of Mechanical Engineering, Islamic Azad university, Iran.
Email: ahmedattaa78@gmail.com

1. INTRODUCTION

One of the most essential structural forms in modern engineering is the thin-walled elastic shell. This is important because it has high stiffness with low weight.Thus, they have a wide application in aerospace, marine, biomedical, automotive, and civil engineering [1]. Due to the coupling of bending and membrane actions the loads are able to distribute across the surface of the whole. The structural efficiency is sensitive to applied loads at certain locations when, in case of local loading, a small concentrated load can induce strong non-linearities, localisation of deformation, .or buckling instabilities [2] . Traditional linear theories can't capture such complex behavior. The resulting outcome can thus only be accurately predicted via nonlinear FE analysis [3].The shell response evolves through several deformation mechanisms under localized loading. At small displacements, bending dominates the response [4]. As deflections increase bending stiffness becomes inadequate, and membrane stretching controls the resistance. This marks the onset of geometric nonlinearity [5]. When large deformations happen, the stresses become very localized in the contact zone and are enhanced by the shell curvature effects [6]. Stress in spherical shells has a tendency to spread radially, whereas in cylindrical shells, the directionality of curvature leads to the development of hoop stress. As a result, the onset of instability occurs later when compared to spherical shells geometries [7].These behavior patterns often occur in practical situations. For instance, aircraft fuselage skins respond to tooling indentation. Submarine hulls respond to underwater impact. Biological membranes respond to mechanical probing. Ignoring nonlinear effects can cause serious errors in predicting stiffness degradation, stress amplification, and post-buckling response of safety-sensitive structures [9]. Thus, unless it is validated through a nonlinear simulation, design cannot be relied upon. The sources of nonlinearity are manifold. The geometric nonlinearity is significant when the displacements are similar in magnitude to the shell thickness. In such cases, the strain-displacement relations become nonlinear and the rotational effects become significant [11]. The link between the reference configuration and the deformed configuration should be updated continuously. Despite the occurrence of material nonlinearity in real structures, the study assumes linear elasticity to isolate the geometric effects [12]. Also, boundary nonlinearity may occur when part of the shell edges are constrained. However, for analytical clarity idealized boundary conditions are commonly used [13].Earlier frameworks such as the Kirchhoff–Love and the Mindlin–Reissner theories of shells were restricted to small-strain/small-rotation cases [14]. For large deformation applications, one must employ fully nonlinear formulations based upon the Green–Lagrange strain tensor and second Piola–Kirchhoff stress in order to achieve true kinematics and energetics [15]. These formulations allow the accurate study of snap-through, post-buckling, and stability loss [16].Ultimately, this study shows the way for future applications that will allow for more realistic inputs into models and future studies. These include material nonlinearity, geometric imperfections, and dynamic loading effects.

2. METHOD

The simulation method used in this study combines nonlinear continuum mechanics, finite element formulation, iterative equilibrium procedures, and geometry-curvature-sensitive discretization to correctly capture the behaviour of elastic shells under concentrated loads. To achieve a proper representation of the geometric nonlinearity, finite strains and high gradient curvature near the loading point, the model was developed. The following subsections present the mathematical formulation, material models, discretization scheme and numerical algorithms used in the nonlinear finite element analysis.

2.1 Nonlinear Continuum Mechanics Formulation

The motion function defines how the shell surface gets deformed when going from the reference/initial configuration to the current deformed one [17]:

$$u + X = x$$

where **X** represents the original position vector and x represents the deformed configuration. For large deformation, the **deformation gradient tensor** is expressed as [18]:

$$\frac{u\partial}{X\partial} + I = \frac{x\partial}{X\partial} = F$$

Finite strain was modeled using the **Green–Lagrange strain tensor**:

$$(I - F^{T} F)\frac{1}{2} = E$$

The strain measure effectively captures large rotations and displacements that characterize elastic shell deformation during indentation.

The stress- strain relationship was established using the second Piola-Kirchhoff stress tensor [19]:

$$E : c = S$$

where the fourth-order constitutive tensor **C** for isotropic elasticity takes the form:

$$\mathbf{C}_{ijkl} = \lambda\delta_{ij}\delta_{kl} + \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})$$

Here, λ and μ are **Lamé constants**, related to Young's modulus $E$and Poisson's ratio v[20]:

$$\frac{E}{(v + 1)^2} = \mu \qquad \frac{E_v}{(1 - 2v)(v + 1)} = \lambda$$

This continuum formulation ensures accurate representation of large deformation behavior.

2.2 Material Properties

The strain measure effectively captures large rotations and displacements that characterize elastic shell deformation during indentation.

The stress- strain relationship was established using the second Piola-Kirchhoff stress tensor[21].

Table 1. Material Properties Used in the Simulation

Property	Symbol	Value	Unit
Young's Modulus	E	70000	MPa
Poisson's Ratio	v	0.33	$-$
Density	p	2700	Kg/m^3
Shear Modulus	$G = \frac{E}{(v+1)^2}$	26,315	MPa

The properties guarantee that the nonlinear response is purely geometric and does not arise from material nonlinearity.

Table 2. Geometric and Finite Element Discretization Parameters of Shell Models

Model	Radius (m)	Thickness (mm)	Element Type	Element Count
Spherical Shell	0.50	4	Quadratic shell (8-node)	6,200
Cylindrical Shell	0.40	5	Quadratic shell (8-node)	5,400

The thickness of the shell is much less than its radius, which is the thin shell structure characteristic. To address highly curved gradients and stress peaks, the load application area mesh was finely tuned.

2.4 Nonlinear Solution Strategy

Equilibrium in the deformed state is governed by [22]:

$$R(u) = F_{ext} - F_{int}(u) = 0$$

The nonlinear problem was solved using the **Newton–Raphson iterative method [23]**:

$$R(u_k) = {}_K K_T(u_k)\Delta u$$

Updated displacements:

$$\Delta u_k + u_k = u_{K+1}$$

To capture **snap-through buckling**, the **arc-length control method** was employed [24]:

$$\Delta s^2 = {}^2\alpha\, {}^2\Delta\lambda + (\Delta u)^T(\Delta u)$$

where $\Delta\lambda$ represents load factor increment and Δs is the arc-length constraint.

This strategy ensures numerical stability even when load decreases while deformation continues to increase.

2.5 Boundary and Loading Conditions

The shell boundaries were fully clamped to restrict rigid body motion. The load was applied gradually to a small circular area at the top center of each shell to create localized indentation that simulates the indentation of an aerospace skin and biomechanical probes. They extended the load increments beyond the first instability point to observe the post-buckling behavior [25].

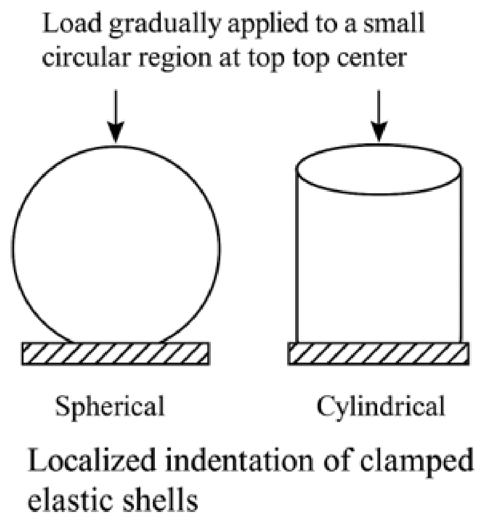

Figure 1. Localized indentation of clamped spherical and cylindrical shells.

2.6 Verification and Numerical Implementation

Mesh sensitivity analysis confirmed solution convergence. The following information was recorded: reaction forces, displacement fields, strain energy components, and curvatures distributions. This made it possible to know when the structure's response changed from bending-dominated to membrane-dominated behavior and where the peak stresses were located near the loaded region [26].

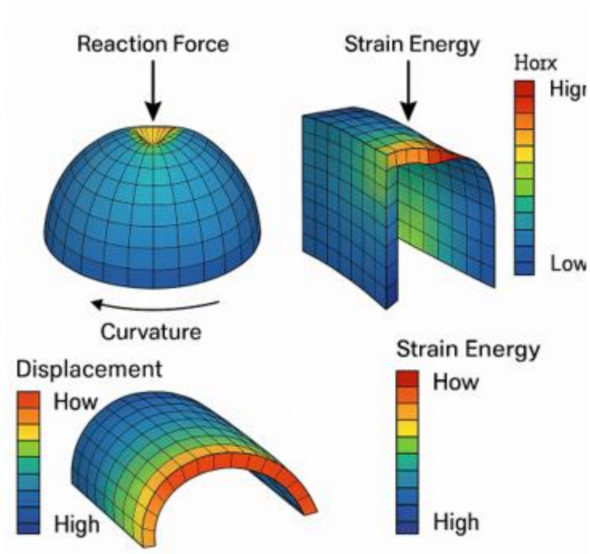

Figure 2. Mesh results under localized loading.

3. RESULTS AND DISCUSSION

The nonlinear finite element analysis provided a detailed understanding of the behavior of a thin elastic shell under concentrated loading as it progresses from a bending-dominated mode of deformation to one that is membrane-dominated with increasing displacements. Furthermore, it reveals the appearance of a localized stress concentration, stiffness decrease, and an unstable snap-through buckling mode. The spherical shell and cylindrical shell models both showed strong nonlinear responses. However, they were found to have notable differences in stiffness evolution, mode of deformation, stress distribution, and energy absorption. The different shapes of these two surfaces - flat and curved - cause the deformation to happen in a different fashion when a pressure is applied.

3.1 Load–Displacement Response

The load-displacement curves of shell configurations show highly nonlinear behaviour at moderate level of displacements. In the beginning, the reply was nearly linear which reflects elastic behaviour of bending. As the indentation deepened, the displacement increased noticeably faster than the force applied, demonstrating geometric nonlinearity. After a set point known as critical load, slope of spherical shell drops suddenly which indicates snap through buckling. After the snap-through point, the system continued to deform under lower or almost constant load, thus confirming instability and post-buckling behavior.Conversely, the cylindrical shell had a less sharp snap-through and a relatively smoother and more gradual stiffness reduction. This shows how stiffness varies when in cylindrical shape. In particular, shells are stiffer in the hoop direction. As a result, the cylindrical shells can take deeper indentations before they become unstable and also exhibit a softer post-buckling response compared to the spherical shells.The below is summary of comparison of important mechanical response parameters.

Table 3. Comparison of Structural Response under Localized Loading

Parameter	Spherical Shell	Cylindrical Shell
Initial stiffness	High	Moderate
Onset of nonlinearity	Early	Intermediate
Buckling behavior	Sharp snap-through	Smooth stiffness reduction
Maximum load before loss of stiffness	Higher	Lower
Post-buckling behavior	Sudden softening	Gradual decline

These results show that spherical shells have a greater resistance to loading than cylindrical shells but will undergo instability earlier than cylindrical shells. In contrast, cylindrical shells deform progressively and distribute deformation more evenly at higher displacement ranges.

3.2 Deformation Modes and Evolution

Visualization if deformation fields revealed changes in structural response At the beginning stage of indentation, the bending deformation prevailed and it was concentrated underneath the loading point. As the displacement increases, the deformation zone expands horizontally and stretching of the membrane is increased. This effect was particularly noticeable in spherical shells, where deformation mostly spread across the curved surface.Over time, a sudden inward “dimple” will form close to the load point in spherical shells, an effect typical of indentation buckling in domes and hollow spheres. After the snap-through, this dimple deepened rapidly. Cylindrical shells, on the other hand, contained long evolution bands along the cylinder axis, revealing their direction stiffness and load-transfer pathway defined by curvature orientation.The deformation patterns here are consistent with well-known experimental results of shell indentations such as the Pogorelov buckling modes, giving credit to the numerical results.

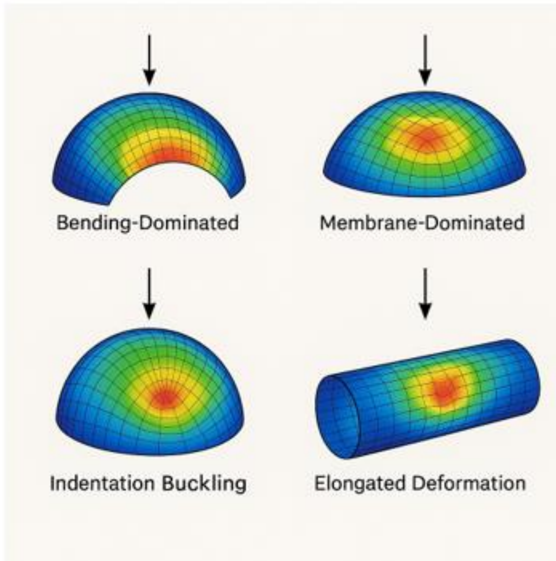

Figure 3: Deformation modes under localized indentation.

3.3 Stress Distribution Characteristics

Stress evolution showed the generation of distinct stress modes with deformation. At small displacements, the stresses were dominated by bending and localised in the loaded region. When the curvature increased, the membrane stresses gained dominance as the stress field spread outward. The spherical shell shows that stress propagates in concentric circles. On the other hand, the stress in the cylindrical shell is in the form of bands that elongate in the hoop direction owing to its circumferential curvature. The area at the load point had the most stress due to the gradient of curvature being sharp. The maximum stresses rose sharply towards the point of instability. Cylindrical shells had a higher value of hoop stress than axial stress which shows that the amplification of hoop stress is the major mechanism of stress when dealing with cylindricals.

Table 4.Maximum von Mises Stress at Various Load Stages

Stage	Spherical Shell Stress (MPa)	Cylindrical Shell Stress (MPa)
Initial elastic stage	38	32
Onset of nonlinearity	92	78
Pre-buckling peak	148	131
Post-buckling	122	118

The stress concentrated near the load point indicates the possibility of failure in the real shell structures which shows the need for non-linear modelling for design safety.

3.4 Energy Absorption and Stiffness Transition

The simulation showed clear changes in the strain energy components. At first, the energy caused by bending strain had the most significance, but as time went on, as more deformation added, the energy caused by the membrane strain became many times larger. This transition took place quite rapidly in spherical shells, featuring a sudden energy jump behind the snap-through point. For cylindrical shells, the energy shift was gradual and continuous due to the smoothening deformation.The total potential energy trends of the two different systems confirm their difference in structural resilience: spherical shells are able to store and release energy during snap-through rapidly, while cylindrical shells are seen to dissipate energy during buckling and deform in a gentler manner. The behavior directly impacts how we design shells and pressure vessels that absorb energy and resist impacts.

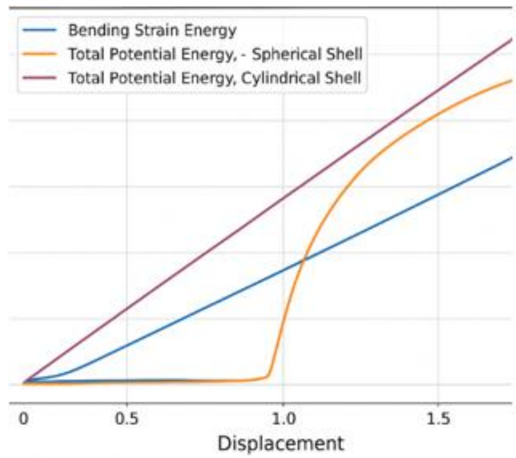

Figure 4: Strain energy transition and total potential energy trends for spherical and cylindrical shells.

3.5 Interpretation and Physical Insight

The results when taken together indicate that the behavior of thin elastic shells under localized load is fundamentally nonlinear. The initial stages of deformation can be modeled using linear shell theory. In the next stage, as the bending capacity becomes fully exploited saturation, the membrane forces become the main active forces responsible for the post-buckling behaviour. Further, this leads to non-linear stiffening or softening. Spherical shells with sharp curvatures may experience more snap-through than ordinary wrinkling modes, where the depressed shape may suggest a rapid transition to a new equilibrium state. This shows the inadequacy of linear analysis for shell design under concentrated loads, and the necessity of nonlinear finite element simulation for obtaining realistic shell mechanics typical of aerospace skins, submarine hulls, biomedical capsules, and the like.

4. Discussion

The nonlinear FE simulation that is prepared in the current study gives a detailed insight into the mechanism of thin elastic shells subjected to a localized load. They show patterns of deformation, stress development, and stability behavior that cannot be captured in linear analytical models. The study shows the comparative performance of spherical and cylindrical shells of identical material and under the same loading conditions. This helps to understand the effect of curvature on stiffness, stability and post-buckling behaviour. Above all, this offers valuable insight into the design of safety-critical structures.The loading is sustained through both bending and membrane actions. At first, the bending stiffness is dominant until certain deformation occurs after which the membrane stresses begins to develop due restraining mechanism which marks the initiation of geometric nonlinearity. So, linear (small-displacement) theory often breaks down. Applied deflection and critical loads are underestimated, which can lead to unsafe design.The spherical shell gave a snap-through instability, in which case the resistance drops suddenly after the peak load. Behaviour well known for shallow domes, this represents a transition between two stable equilibrium states. Even when the material is still elastic, its geometry becomes reconfigured, resulting in the rapid discharge of stored bending energy. This phenomenon is critical in various types of pressure vessels, in aerospace domes and in protective shells, among others. Their unloading can cause a dramatic release of energy, leading to catastrophic failure.In stark contrast, cylindrical sheets did not suddenly collapse, instead, they exhibited stiffness decay. Because a cylinder has curvature in only one principal direction it exhibits anisotropic load transfer (higher hoop stiffness than axial stiffness) which allows its deformation to distribute smoothly. Pipelines, fuselages, and tanks deform in a progressive fashion; hence they can be inspected. Spherical shells have a higher initial stiffness while cylindrical shells have more stable and ductile-like deformation paths.Stress-field visualization found severe stress concentration near load application zone. In spherical shells, the stresses radiated through the body but in the case of cylindrical shells, stresses concentrated along circumferences. According to classical shell theory, higher hoop stress appeared in the latter. The anisotropic stress behavior is important for submarine hulls and other underwaterstructures that experience localized impacts producing ring-like stresses that cause cracks.The analysis of strain energy clarified the deformation mechanism. It started with energy storage dominated by bending. Then, with the increase of displacement, the energy storage transitioned to being dominated by the membrane. The quick change of spherical shells indicates sudden energy redistribution, called a snap-through. Recognizing these energy paths helps produce impact-resistant, crashworthy and resilient structures by choosing geometries to absorb energy without collapsing.

The Newton–Raphson iterative solver used with arc-length control was necessary to accurately estimate the pre-and post-buckling behaviour. Conventional linear or incremental schemes which were employed beyond peak loads broke down. This failure proved that nonlinear solvers are essential for tracing stability as well as the correct prediction of the structural behaviour.Although the research was confined to elastic materials, in real systems, plasticity, contact effects, or loading condition could exist. The deformation of biological and polymeric membranes is nonlinear, which gives rise to either viscoelasticity or hyperelasticity. While isolating geometric nonlinearity improved clarity, it would be worthwhile in future work to add material and boundary nonlinearities to represent a more realistic service environment comprising thermal, pressure, and fatigue effects. From the design perspective, geometry choice is function-specific. There are special spheres that are good at resisting deep indentations. However, there is a risk that they will fail quickly. Cylindrical cells are preferred when the need to deform gradually is required. Also, the ability to inspect them is very important. “Curvature is not just a geometric property but a performance attribute”.

5. CONCLUSION

This nonlinear finite element study provides a comprehensive understanding of thin elastic shells under localized loading, stressing the dominance of geometric nonlinearity. Examining spherical shells and cylindrical shells under indentation reveals differences on how their stiffness responds and deformation proceeds, as well as their stability behaviour. Thus, linear elastic theory would not suffice to predict large deformation behaviour.Both shell types initially resist loads through bending, but as the indentation deepens, membrane stretching controls the response, resulting in degradation of stiffness and nonlinear load–displacement behaviour. The spherical shell experienced a snap-through instability, which is sudden jump from an equilibrium state to another. This is a concern in structures like a dome or pressure vessel where a sudden loss of load bearing capacity can occur. On the contrary, the cylindrical shell began to exhibit decreasing stiffness which lead to more smooth deformation and predictable behaviour. This is very beneficial in the case of pipeline and fuselages. According to classical shell theory, radial stress propagates in spherical shells while hoop stress concentrates in cylindrical shells, which is curvature dependent. Energy shifted from being bent-dominated to membrane-dominated, showing how geometry controls energy reconfiguration.The simulation results confirmed that post-buckling and instability behavior can be captured through nonlinear FE methods with updated Lagrangian and arc-length control. The relevant study illustrates the necessity of using nonlinear modelling to design lightweight, safe shell structures in engineering disciplines.

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BIOGRAPHIES OF AUTHORS

Ahmed Attaa Neamah is a mechanical engineer specializing in applied design. He holds a Master's degree in Mechanical Engineering (Applied Design) from the Islamic Azad University, Iran. His academic and professional interests focus on mechanical system design, analysis, and optimization, with strong expertise in engineering applications and problem-solving in mechanical design fields.