

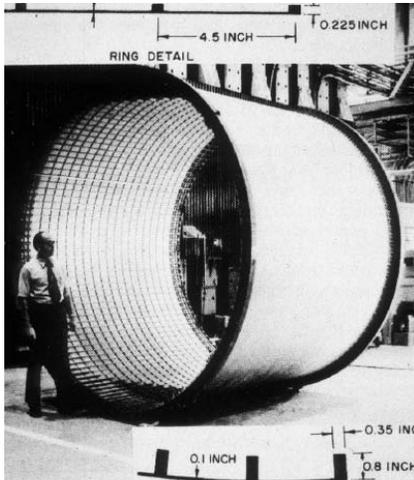
Buckles, Creases & Wrinkles

In shell structures & soft materials

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Shell structures: Buckling & catastrophic collapse



Stiffened cylindrical shell for space rocket (NASA)



Unstiffened spherical shell for LNG tanker

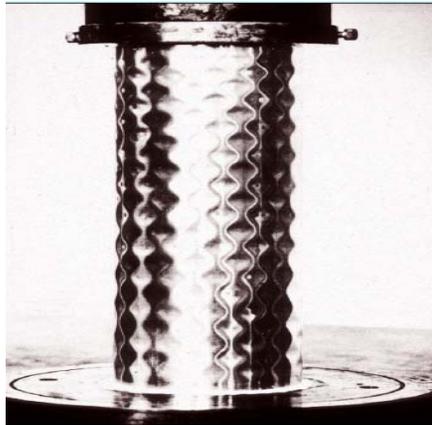


Buckled & collapsed cylindrical shell water tower

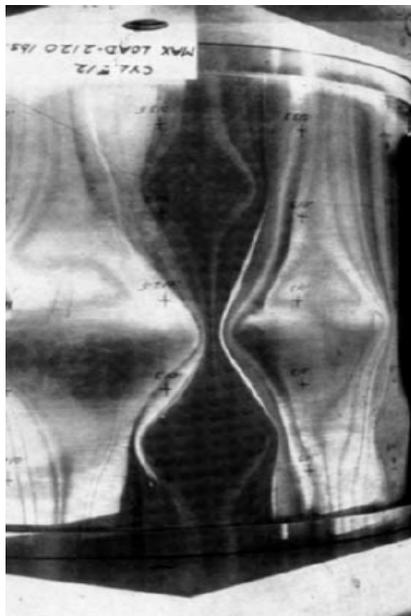


Buckled huge steel wine barrel in CA failed during earthquake

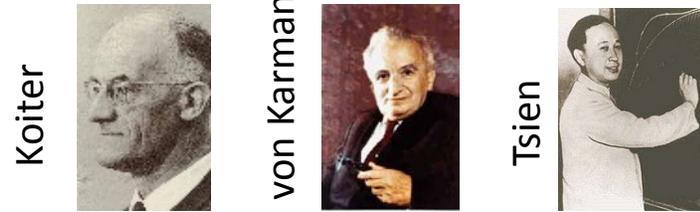
The highly unstable and imperfection-sensitive buckling behavior of shells



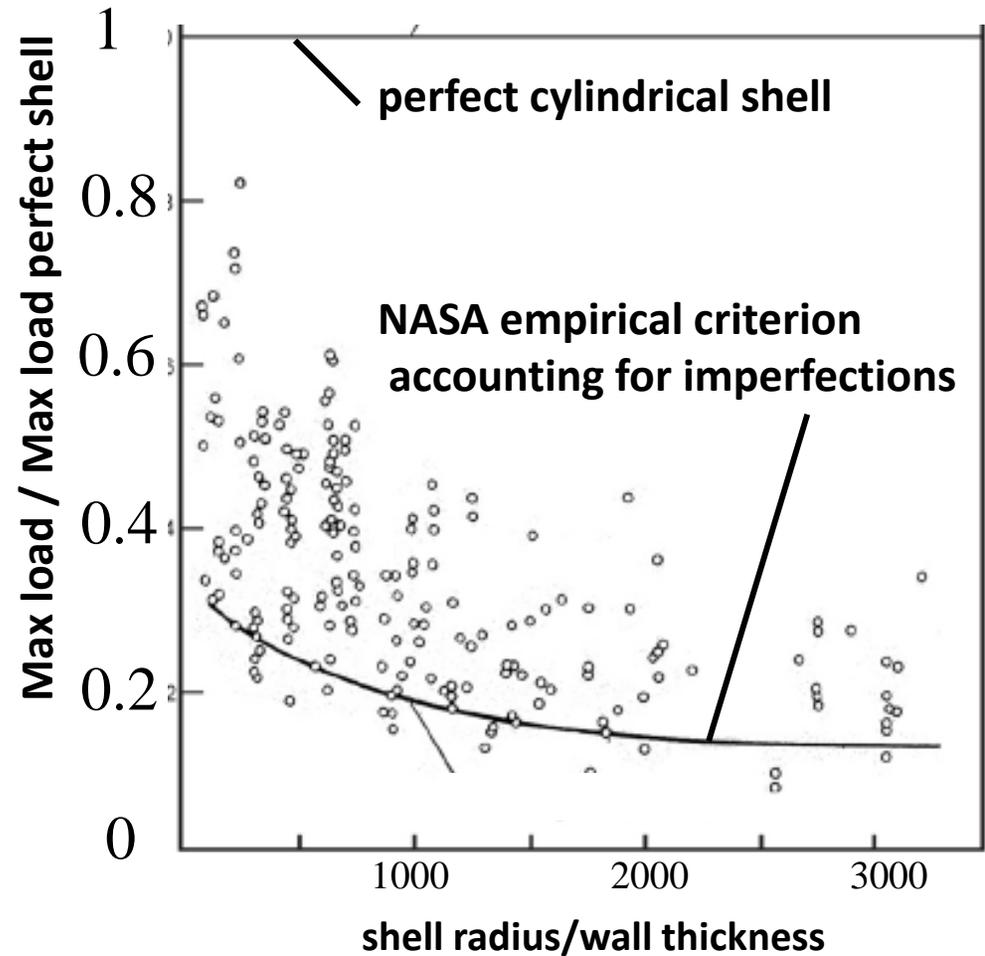
Short wavelength mode:
arrested by internal mandrel



Long wavelength mode
seen in collapsed state



Major early contributors to nonlinear shell buckling

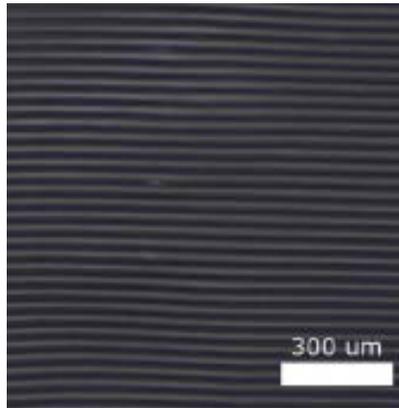


Buckling loads for actual shells

Wrinkling & Creasing of Compressed Soft Materials (Elastomers & Gels)

WRINKLING

Systems with thin stiff film



Sinusoidal wrinkling of stiff thin film on compliant substrate compressed in vertical direction.



Herringbone wrinkling of stiff gold film on compliant substrate compressed equi-biaxially.

CREASING

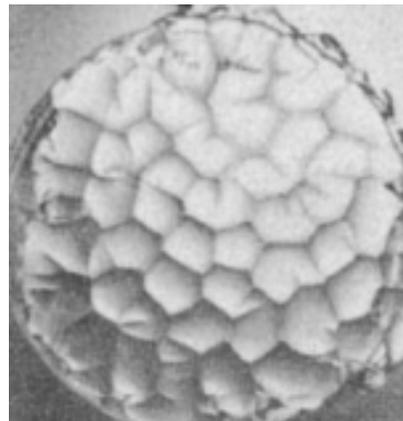
Homogeneous substrates with no films



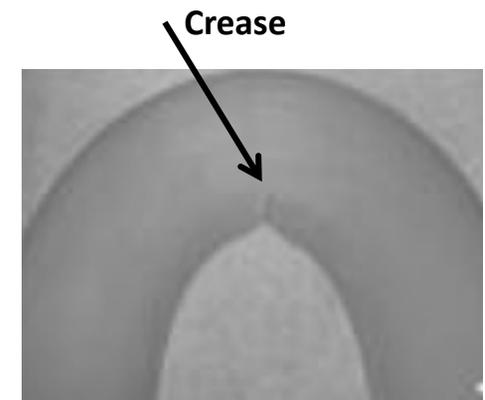
Creases (sulci) on surface of human brain (compressed by growth nearly equi-biaxially)



Crease on surface of a homogeneous gel (Jello) compressed horizontally between hands.



Creases on surface of a swelling gel constrained within a circular container



Crease on the compressive side of a bent rubber bar

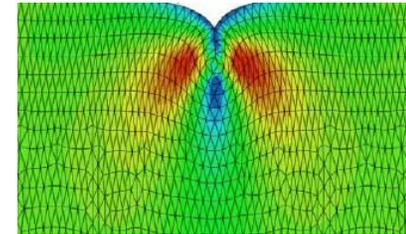
Why are creases, but never wrinkles, observed on the surface of compressed homogeneous elastomers and gels?



Biot



Wrinkling



Creasing

In 1962, Biot carried out a linearized stability analysis of a compressed elastomer half-space and determined that a surface wrinkling mode is expected at a compression of 45% (for a neo-Hookean material).

The wrinkling mode has never been observed in experiments. Instead, at a compressive strain of about 35% creases on the surface are observed.

Biot's work is mathematically correct, Contributions in the past few years [Hohlfeld & Mahadevan(2008,2011), Hong, Zhao & Suo(2009), Cao & Hutchinson(2012)] have shown that the wrinkling mode is **highly unstable and imperfection-sensitive**. Creases are finite strain modes which are energetically favorable at compressive strains above 35%. Creases are not predicted by classical linearized stability analysis.

Surface wrinkles are not observed because, owing to small imperfections, they localize at extremely small amplitudes and collapse to creases, analogous to the fact that the cylindrical shell collapses to the long wavelength mode without evidence of the short wavelength mode having appeared.

Moving Forward for Shells & Soft Materials:

For Shell Buckling, NASA has recently launched an effort to reduce reliance on empirical design by:

- 1) Measuring and characterizing shell imperfections
- 2) Computing buckling loads for the imperfect shells
- 3) Establishing validity by experiments



For Soft Materials, all the evidence suggests we must live with the possibility of creasing instabilities and design against (or for) them.

- 1) Creases fall outside the scope of classical linearized stability analysis.
- 2) They are finite strain modes triggered by small imperfections.
- 3) The scale of the creases (and wrinkles) is not set by the continuum theory —additional physics enters.