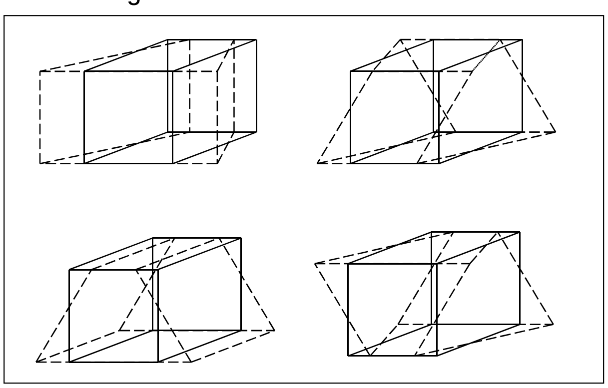
Hourglass (HG) Modes

- Hourglass modes are nonphysical modes of deformation that occur in underintegrated elements and produce no stress. By underintegrated, we mean…
  - Solid elements with a single integration point
  - Shell or Tshell elements with a single in-plane integration point

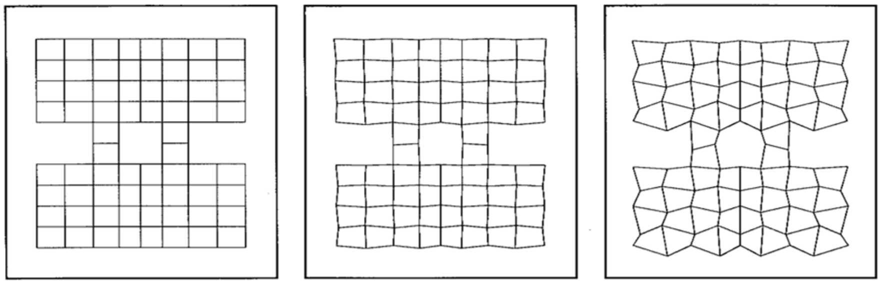
- One point integration is much faster so we usually tolerate, but try to minimize, hourglass modes.
  - Hourglassing can usually be controlled by applying internal forces to resist hourglass modes via one of several HG control algorithms.
  - Hourglass energy, which is work done by the forces calculated to resist hourglass modes, takes away from physical energy of the system.

Hourglassing

- **Hourglassing modes**
  - Underintegrated solids have 12 HG modes
    - 4 such modes are shown below
  - Underintegrated shells have 5 HG modes



Hourglass Modes in Shells



Case 1
No hourglassing evident

Case 2
Moderate to severe hourglassing

Case 2 with
Displacements scaled up

Severe hourglassing may be apparent without scaling displacements.

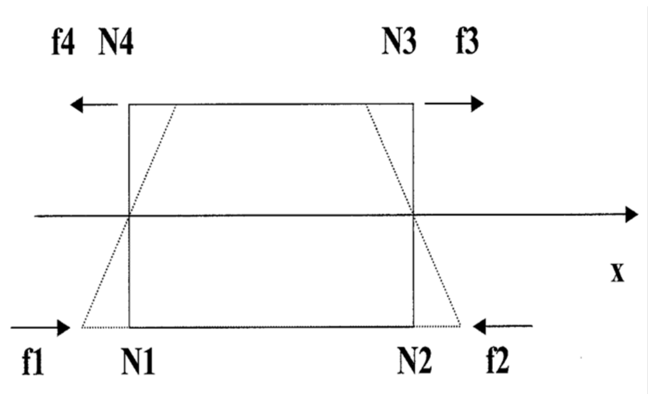
To visualize moderate hourglassing, one might need to scale up displacements (via *Setting* button in LS-Prepost)

Avoiding or Minimizing Hourglass Modes

- Fully integrated solids and shells do <u>not</u> hourglass
  - Full integration is more expensive
  - Fully integrated elements can be less robust for large deformations
- Tetrahedrons and triangles do <u>not</u> hourglass
  - Generally not recommended due to locking tendencies
- For elements that <u>are</u> susceptible to hourglass modes, internal hourglass forces are applied to resist the hourglass mode deformation
  - There are several algorithms (hourglass formulations) available for computing these forces

Hourglass Forces Resist HG Modes

- Introduce internal nodal forces to counteract hourglass modes



Stiffness vs. Viscous Forms of Hourglass Control

- Viscous forms generate hourglass forces proportional to components of nodal velocity contributing to hourglass modes.
  - Inhibits additional hourglassing deformation (can't recover from previously accumulated HG deformation)
  - Viscous forms recommended for high velocity/high strain rate problems, e.g., those involving high explosives.
- Stiffness forms generate hourglass forces proportional to components of nodal displacement contributing to hourglass modes.
  - Able to reduce total accumulated hourglassing deformation
  - Preferred for lower rate problems, including crash simulation
  - Stiffness forms may artificially stiffen response. Therefore, reduce hourglass coefficient, say from .10 to .03, to minimize stiffening effect.

Hourglass Control for Solids

- 3 forms of viscous HG control for solids
  - Hourglass coefficient should be less than 0.15
  - Type 1: standard (cheapest)
  - Type 2: Flanagan-Belytschko (default)
  - Type 3: Flanagan-Belytschko with exact volume integration (better for skewed elements)
- 2 forms of stiffness HG control for solids
  - Hourglass coefficient should not exceed 0.1; 0.03 is better
  - Type 4: Flanagan-Belytschko
  - Type 5: Flanagan-Belytschko with exact volume integration
- Types 6, 7, 9, 10 (see next 2 slides)
  - Hourglass coefficient can range from 0.1 to 1.0

Hourglass Control for Solids (cont'd)

- Type 6 is an assumed strain, co-rotational stiffness formulation by Belytschko-Bindeman [1993]
  - An assumed strain field and the material's elastic properties are used to calculate an assumed stress field. That stress field is integrated in closed form over the element domain to develop hourglass forces such that element behaves as a fully integrated element.
  - For materials which soften, an hourglass coefficient of 0.1 or less is suggested.
  - Interesting fact: When used with elastic material and a hourglass coefficient of 1.0, bending stiffness of a part is correctly modeled using only a single layer of solid elements.
  - Typically more effective than HG types 1-5 when…
    - Elements have large aspect ratios (>2)
    - Elements start off or become significantly skewed
    - Material is very soft (foam, honeycomb, rubber)

Hourglass Control for Solids (cont'd)

- Type 7 HG control is a variation of Type 6 which compares the deformed geometry to the original geometry in calculating the HG forces
  - Type 6 is incremental hourglass approach; 7 is total hourglass approach and therefore not path dependent
  - Developed to correct problem of spinning tires not returning to undeformed configuration when unloaded
  - Type 7 strongly recommended for foams having *INTIAL_FOAM_REFERENCE_GEOMETRY
  - Good for Visco-Elastic materials
  - 2x as expensive as type 6
- Type 9 HG control (Puso) may be thought of as an enhanced Type 6
  - For MATs 3,18, and 24, negative values of hourglass coeffient trigger use of current (not initial) material properties in computing HG forces
  - May be better than type 6 for distorted or skewed elements
- Type 10 (Cosserat) is new. Early indications show superior accuracy for small deformation problems.

Hourglass Control for Shells

- One form of <u>viscous</u> HG control for shells
  - IHQ = 1, 2, and 3 are identical
- One form of <u>stiffness</u> HG control for shells
  - IHQ = 4, 5, and 6 are identical
- IHQ=8 invokes warping stiffness for fully-integrated shell formulation 16
  - Correctly solves twisted beam problem

Keywords Related to Hourglassing

- *CONTROL_HOURGLASS
  - Sets global hourglass formulation and coefficient
- *HOURGLASS
  - Sets hourglass formulation and coefficient for specific parts (overrides global setting)
  - Must also set HGID in *PART
- *CONTROL_ENERGY
  - Set HGEN to 2 to have hourglass energy calculated (recommended)
- *DATABASE_GLSTAT, *DATABASE_MATSUM
  - Hourglass energy written to glstat and matsum files
- *DATABASE_EXTENT_BINARY
  - Set SHGE = 2 to be able to fringe hourglass energy in shells

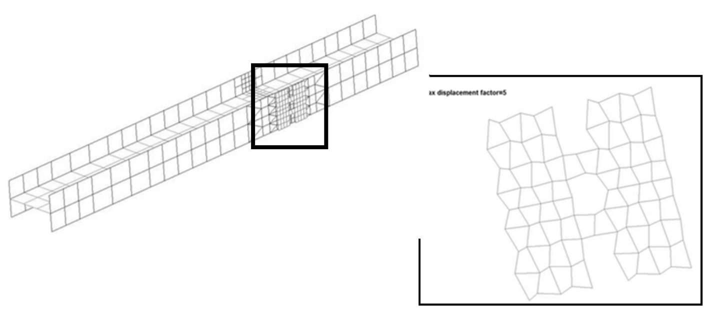
Guidelines

- Rule of thumb: HG energy should be < 10% of internal energy. This should hold for:
  - Whole system (check the *glstat* file)
  - Each part (check the *matsum* file)
    - Moderate to severe hourglassing may be judged acceptable in coarsely meshed parts away from primary area of interest
- Apply pressures rather than concentrated nodal forces (less tendency to excite hourglass modes)

Guidelines

- For fluids (low or zero shear strength), recommend hourglass formulation 1 (default) with an hourglass coefficient = 1e-3 or less
- Goal is to keep hourglass deformation *and* hourglass energy to tolerable levels. Things that will help:
  - Refining mesh
  - Selecting an appropriate hourglass formulation and coefficient for each part that uses underintegrated element formulations
  - Changing to a fully integrated element formulation
    - For shells, change to fully integrated formulation 16 and set hourglass type to 8
    - For solids, fully integrated elements may not be a good solution

Exercise 5



- Investigate model to check hourglass.
- Improve model to avoid hourglass.
- See influence from changing hourglass parameters.