Hourglass (HG) Modes

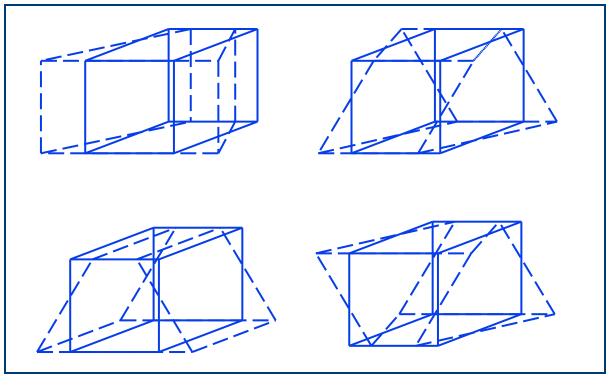
- Hourglass modes are nonphysical modes of deformation that occur in underintegrated elements and produce no stress. By underintegrated, we mean…
  - Solid elements with a single integration point
  - Shell or Tshell elements with a single in-plane integration point

Hourglass (HG) Modes

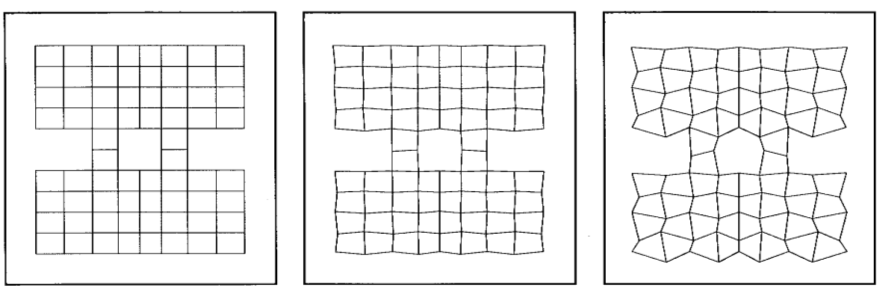
- Single point integration is much faster than full integration.
- Underintegrated elements are often more stable under large states of deformation.
- BUT the hourglassing modes that go along with these element types must be kept in check.
  - Hourglassing can be kept in check by invoking a suitable HG control algorithm that creates internal forces to resist hourglass modes.
  - Hourglass energy, which is work done by the internal forces applied to resist hourglass modes, is is dissipative in nature. In this regard, it’s like damping except that it’s nonphysical and so we want to keep it to a minimum.

Hourglass 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

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

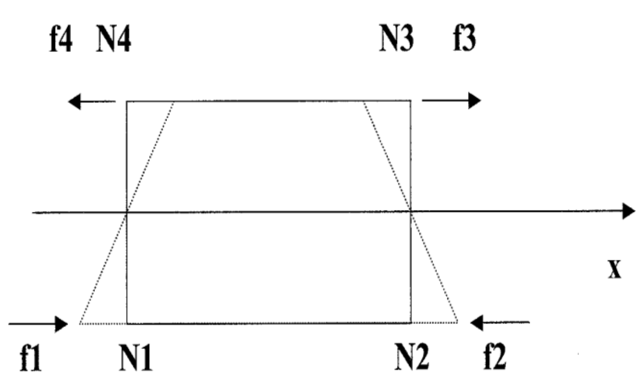
Severe hourglassing may be apparent without scaling displacements.

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
  - But these element shapes often having locking tendencies or otherwise are less desireable than bricks (hexahedrons) and quads
- The coarser the mesh, the more susceptible the elements are to hourglassing
- For elements that are subject to hourglass modes, select a suitable hourglass control algorithm and hourglass coefficient

Hourglass Control Algorithm

- The hourglass control algorithm applies internal nodal forces to counteract hourglass modes



Stiffness vs. Viscous Forms of Hourglass Control

- **Viscous** forms of hourglass control
  - Generate hourglass forces proportional to components of nodal velocity contributing to hourglass modes.
  - Inhibit additional hourglassing deformation but can't recover from previously accumulated HG deformation
  - Viscous forms of hourglass control are recommended for high velocity/high strain rate problems, e.g., those involving high explosives.
- **Stiffness** forms of hourglass control
  - 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
  - While often more effective at keeping hourglassing in check than viscous forms, stiffness forms may artificially stiffen response. Therefore, reduce hourglass coefficient, say from 0.10 to 0.03, to minimize stiffening effect.

Hourglass Control for Solids

- 3 forms of viscous HG control for solids
  - Hourglass coefficient should be less than 0.15 (default=0.10)
  - 1: standard (cheapest, generally not recommended)
  - 2: Flanagan-Belytschko (default)
  - 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
  - 4: Flanagan-Belytschko
  - 5: Flanagan-Belytschko with exact volume integration
- Newer forms 6, 7, 9, 10 for solids (see next 2 slides)
  - Hourglass coefficient can range from 0.1 to 1.0

Hourglass Control for Solids (cont'd)

- Type 6 HG control 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 the element behaves as a fully integrated element.
  - For plasticity-based materials, an hourglass coefficient of 0.1 or less is suggested.
  - Interesting fact: When used with an elastic material and a hourglass coefficient of 1.0, bending stiffness of a part is correctly modeled using only a single layer of underintegrated 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 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) may provide better accuracy for small deformation problems.

Hourglass Control for Shells

- Only one form of viscous HG control for shells
  - IHQ = 1, 2, and 3 are identical
- Only one form of stiffness HG control for shells
  - IHQ = 4, 5, and 6 are identical
- HG form 8 invokes warping stiffness for fully-integrated shell formulation 16
  - Applies only to shell formulation 16 and is recommended for shell formulation 16

Keywords Related to Hourglassing

- ***CONTROL_HOURGLASS**
  - Sets default hourglass formulation and coefficient
- ***HOURGLASS**
  - Sets hourglass formulation and coefficient for specific parts (overrides default settings)
  - 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

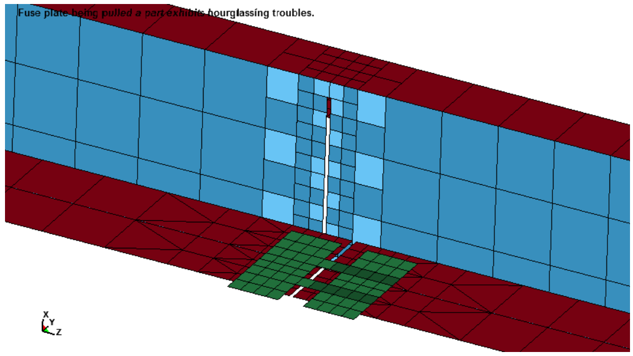
Guidelines

- *Rule of thumb*: HG energy should be < 10% of internal energy. This rule applies to the…
  - Whole system (check the *glstat* file)
  - Each part (check the *matsum* file)
- Observed hourglassing modes 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 reduce hourglassing.
- See influence from changing hourglass parameters.