The CAESAR II Piping Model

How Good Is It?

Quick Agenda

- Introduction
- The digital model
- What’s missing in our CAESAR II model?
- Model precision and construction tolerances
- Engineering Sensitivity
- Boundary Conditions
- Modeling Choices
- Model Verification

INTERGRAPH

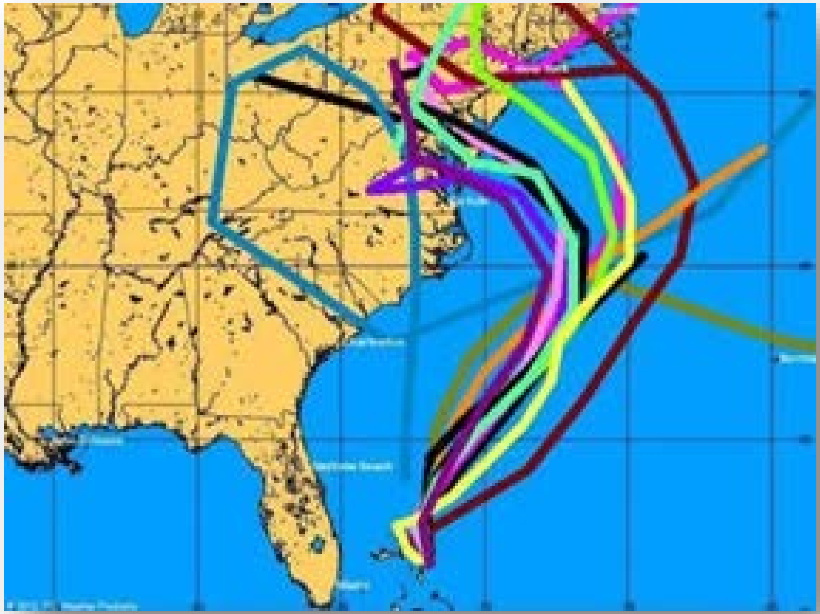
All Models are Wrong.

- "The statistician George Box warned that "All models are wrong, but some are useful." Every model is only an approximation. They are only shadows of reality. They are wrong — no shadow captures all the complexities of the real thing. However, stripped of distracting hues and facets such shadows are easier to manipulate in our mind. Models allow us to make sense of the world."

Episode No. 2707, Engines of Our Ingenuity – University of Houston

Models for Hurricane Sandy

- Proposed Tracks for Hurricane Sandy, October 2012



- Which one was “right”?

What does the B31.3 Piping Code say?

- 319.4.2 Formal [Flexibility] Analysis Requirements

  (c) Acceptable comprehensive methods of analysis include analytical and chart methods which provide an evaluation of the forces, moments, and stresses caused by displacement strains (see para. 319.2.1).

  (d) Comprehensive analysis shall take into account stress intensification factors for any component other than straight pipe. Credit may be taken for the extra flexibility of such a component.

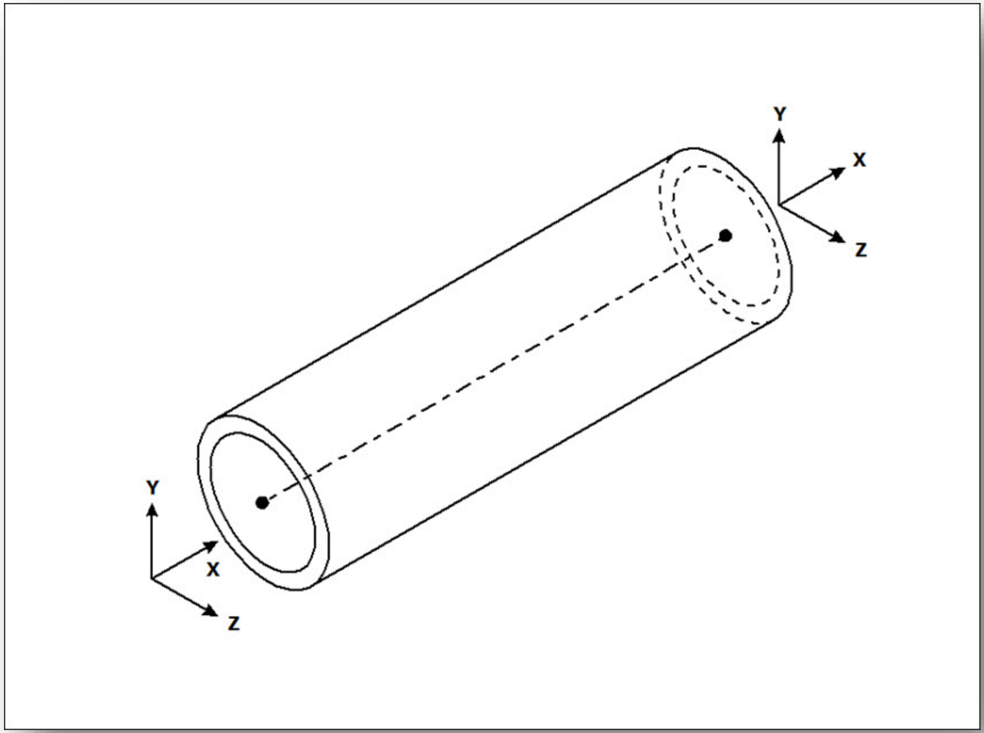
A System Model

- We are evaluating the interaction of piping components and their loads
- Think of this as if you are viewing the piping system that is “across the street” rather than up close with a magnifying glass
  - We can’t say where specifically a through the wall crack will form, but
  - We can identify the system as safe or unsafe
- This system model is composed of <u>beams in bending</u>
  - This is an efficient form of analysis
  - This is sufficient for <u>system</u> analysis

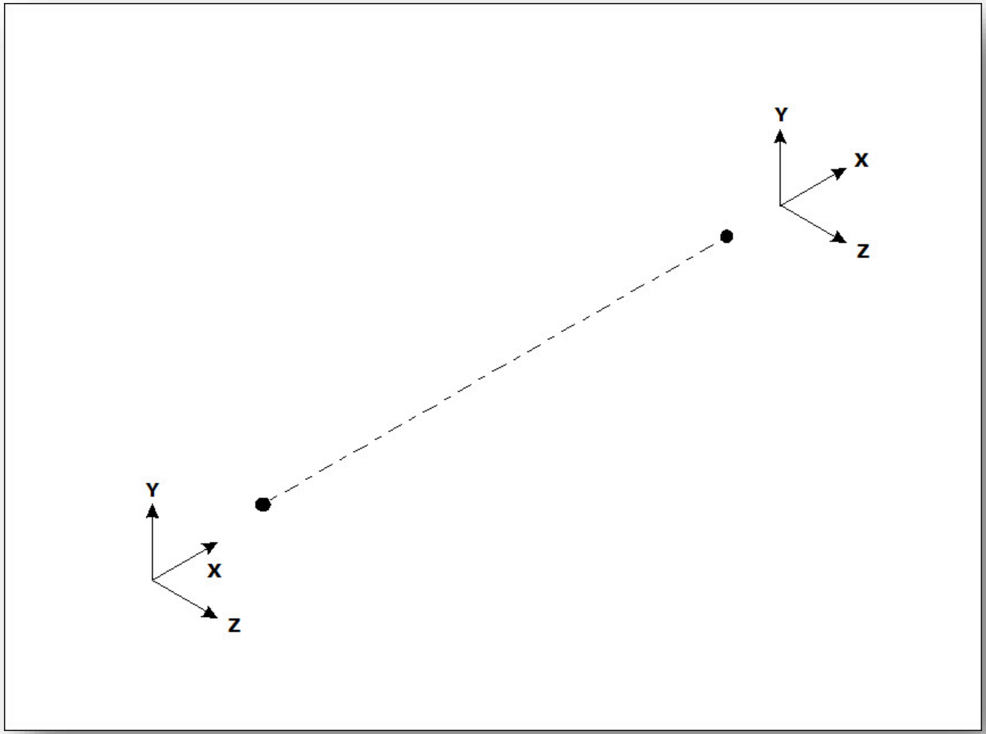
Analog versus Digital Representation

- Our initial image is analog
  - A sketch, drawing, illustration, schematic
  - A continuous assembly of various physical elements which make up the system
- The computer model is digital
  - The system is collection of simple beam elements which represent the piping components
  - These beam elements represent the stiffness of each element
  - This assembly of interacting beam elements and the system supports take the form of a stiffness matrix [K]
  - The system response to any applied load {F} or displacement {X} can be defined using the relationship {F}=[K]{X}.
  - The stiffness matrix translates system information – this “information” is load and position
  - But this information is collected or reported only at the end of each beam element.

3D Beam Element

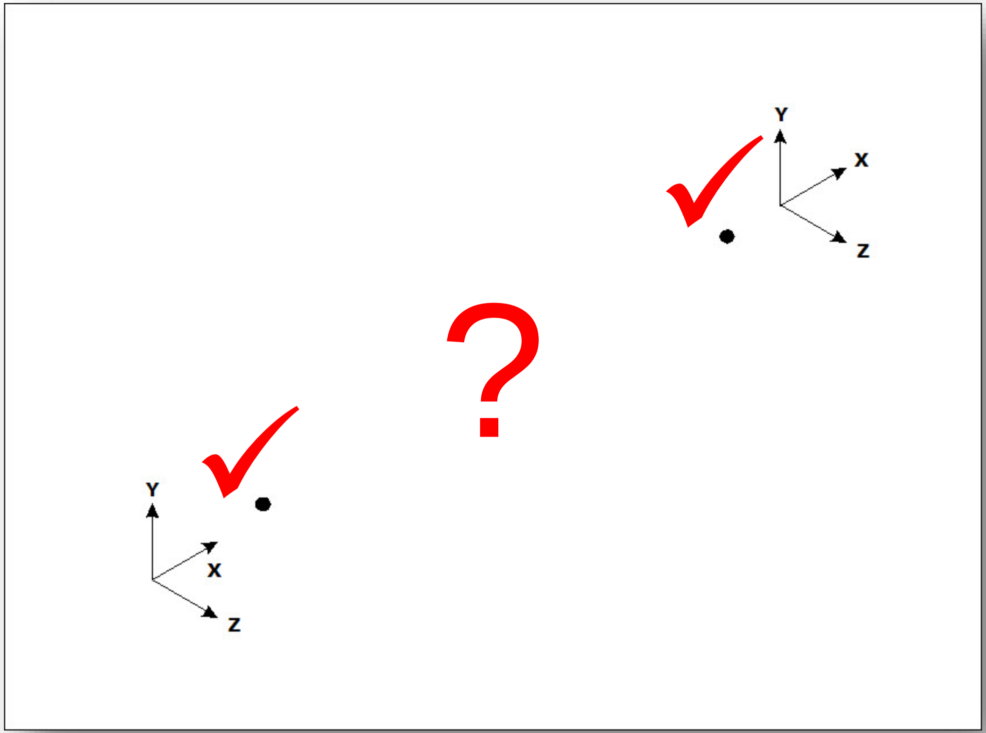


3D Beam Element



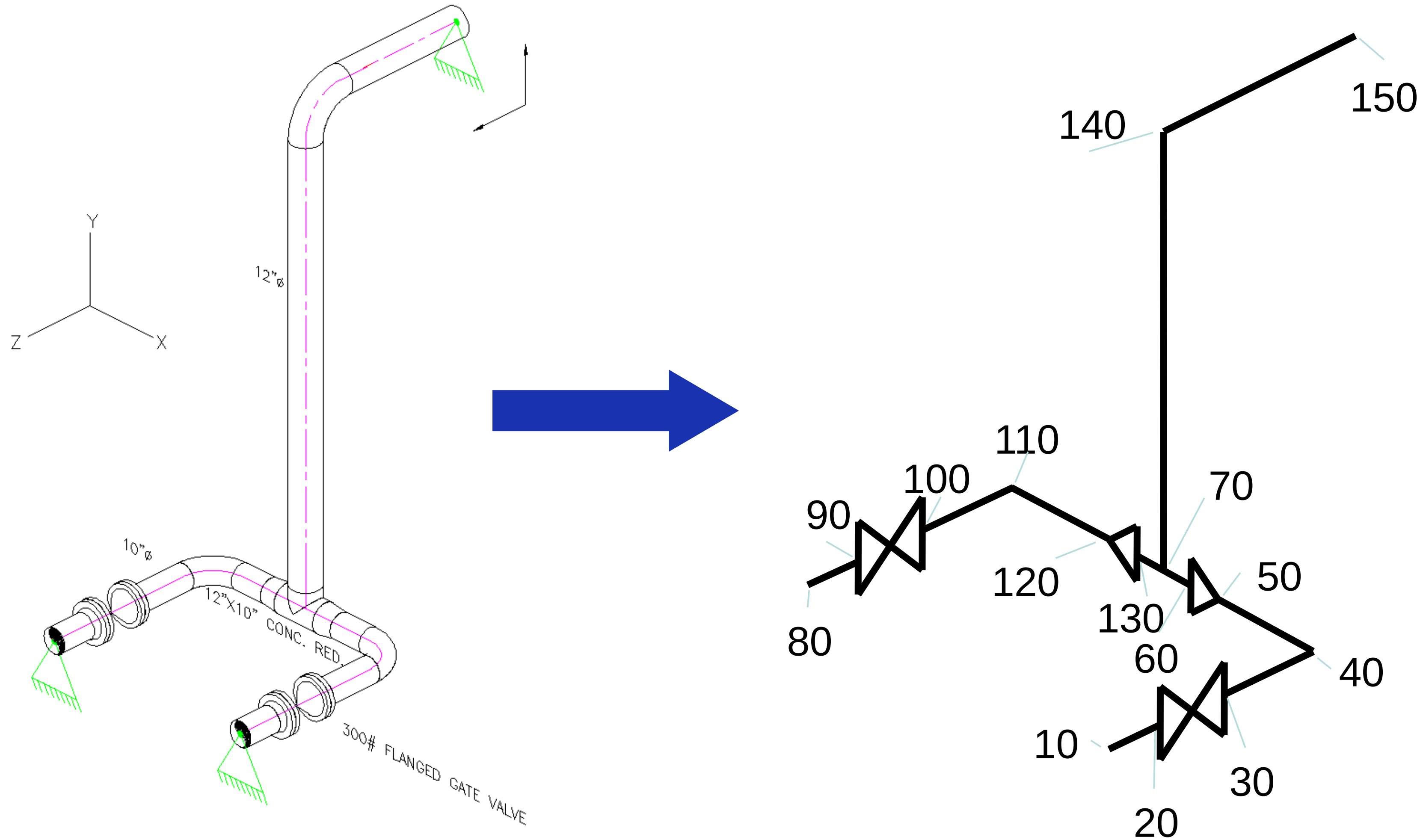
- CAESAR II has no continuous shell

3D Beam Element



- CAESAR II has no continuous shell
- CAESAR II doesn't even have a centerline
- CAESAR II only has endpoints
- But that's OK for a system model

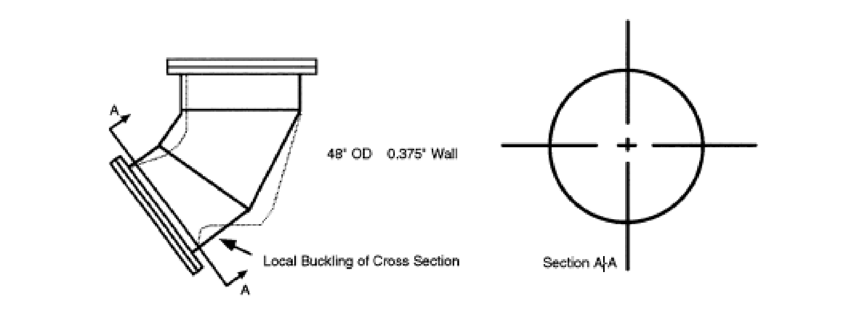
Analog versus Digital Representation



INTERGRAPH

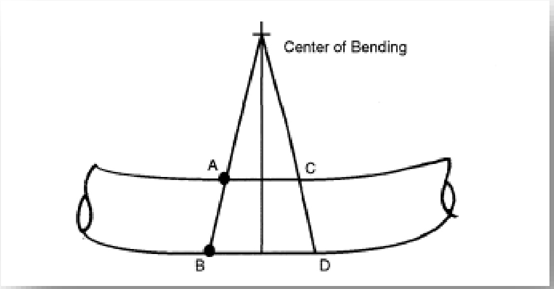
What is Assumed in this Centerline (or Stick) Model?

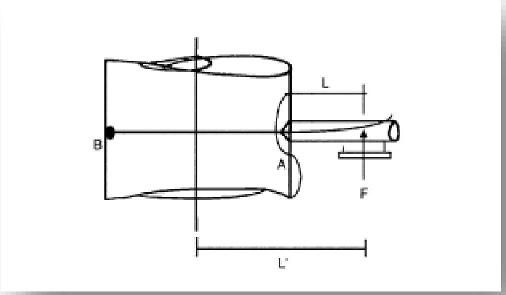
1. All elements remain stable under load
   - Local buckling of cross-sections is ignored
   - Bending occurs before wall deformation
   - The analysis expects "long, skinny" cantilevers, not short elements with a large D/t ratio



What is Assumed?

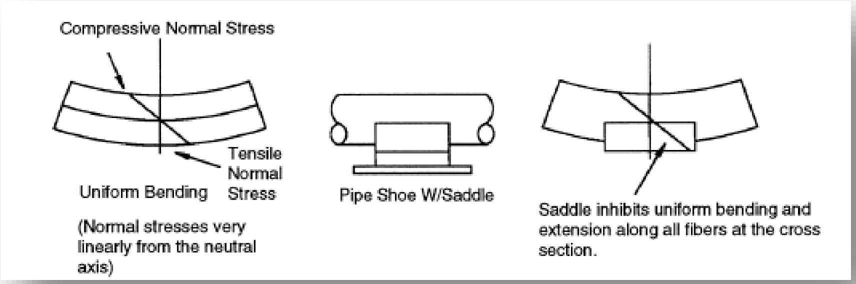
2. Plane sections remain plane
   - Algorithm assumes that points A and B (left figure) always lie on the same cross-sectional plane, whether in the deformed or the un-deformed state
   - The moment F x L (right figure) does not produce a uniform "plane sections-remain-plane" bending load at the cross-section A-B, since it causes local warping





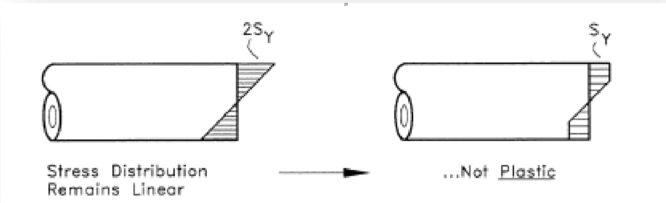
What is Assumed?

3. Hooke's Law is applicable across all fibers of the cross-section



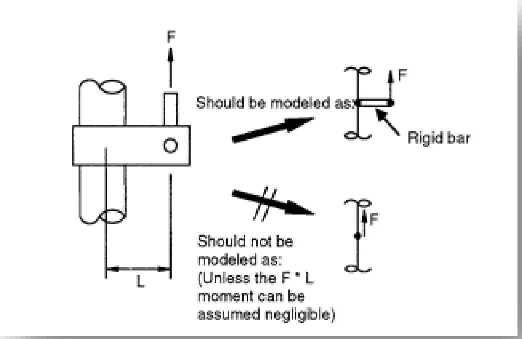
What is Assumed?

4. Hooke's Law is applicable throughout the entire load range
   - No plastic response



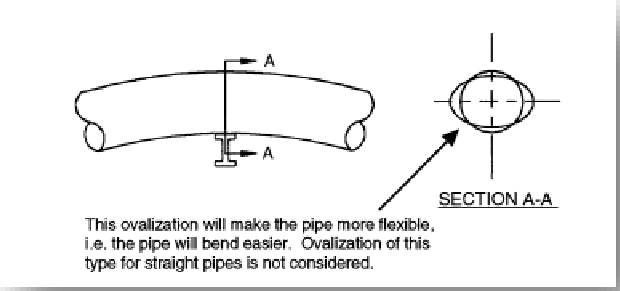
What is Assumed?

5. Moments and forces applied to the beam are assumed to act about the neutral axis
   - Centerline support, no shell/wall



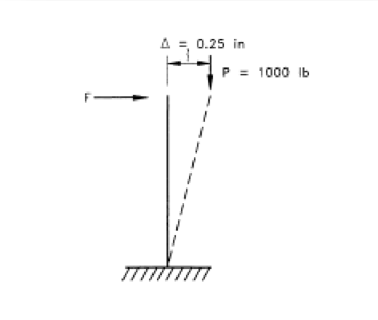
What is Assumed?

6. Element cross-sections do not ovalize under load (except as adjusted for bend elements)
   - The stresses at the ovalized section are intensified due to:
     - Reduction in section modulus, and
     - Added local plate bending in the top and bottom fibers



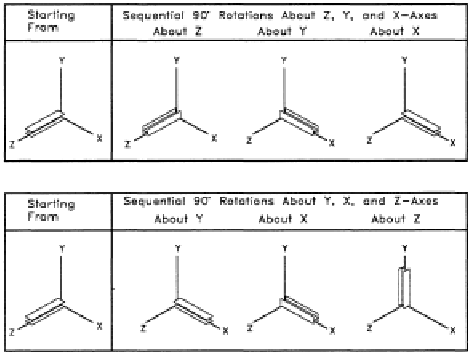
What is Assumed?

7. Applied loads are not affected by the deformed state of the structure (P-delta effect)
   - In the figure below a 1000 lbf load is placed at the top of a riser. A wind load shifts the top by ¼ inch. Realistically, there will be an additional moment applied to the system, equal to the load times its displaced distance from the neutral axis of the structure (i.e., 1000 lbf x 0.25 inches = 250 in-lb).
   - All loads are applied based on the original pipe position.



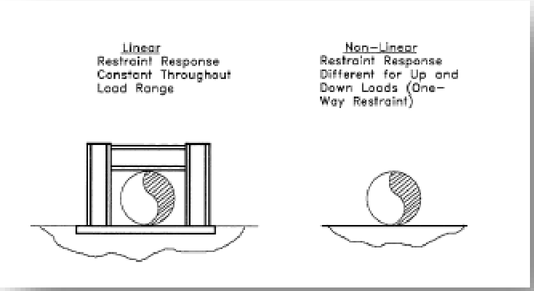
What is Assumed?

8. Rotational deformations of the system are assumed to be small
   - Node point rotations are added as vectors in CAESAR II.
   - Rotations in 3 dimensions are not communative, that is, combining rotation is order dependent – the figure below shows two different sequences in combining three 90 degree rotations.
   - Rotation is defined as angulation about some vector defined for the system under evaluation. The vector is defined relative to the system so as the system moves, so should the vector. In CAESAR II matrix operations, these vectors do not reorient based on system movement under load.
   - Errors become significant as rotations increase. Note that most rotation in CAESAR II is less than 1 or 2 degrees. This is acceptable. Be aware of <u>large</u> rotation.
   - Another way of saying this is CAESAR II does not use geometric constraint. CAESAR II is not a linkage program.



What is Assumed?

9. Boundary conditions are assumed to respond in a linear fashion
   - The stiffness algorithm cannot solve for non-linear restraint conditions, such as one-directional restraints, bi-linear restraints (soil or bottomed out springs), friction, etc.
   - CAESAR II's iterative procedure iterates through linear solutions until all defined nonlinear restraints respond properly for that static load case.



What Models/Analyses are Susceptible to these Deficiencies?

1. Large Diameter/thin wall piping or ducts
   - In this case, it is advisable to minimize localized loadings by distributing them with pads or saddles, or do plate buckling analysis (preferably with finite element software) when the loads cannot be altered.
   - Note (1) from ASME B31.3 Appendix D states that flexibility and stress intensification factors are valid for D/T<100:

Table D300[1] Flexibility Factor, *k*, and Stress Intensification Factor, *i* (Cont'd) (12)

NOTES:

(1) Stress intensification and flexibility factor data in Table D300 are for use in the absence of more directly applicable data (see para. 319.3.6). Their validity has been demonstrated for $D/\overline{T} \leq 100$.

(2) The flexibility factor, *k*, in the Table applies to bending in any plane; also see para. 319.3.6. The flexibility factors, *k*, and stress

What Models/Analyses are Susceptible to these Deficiencies?

2. Localized stress conditions for situations not explicitly covered by a stress intensification factor, e.g., a saddle
   - The portion of the pipe impacted by the saddle may be modeled as a rigid element, while saddle/piping local stresses may be estimated through the use of finite element analysis (FEA) or through the use of Welding Research Council Bulletins, such as 107 and 297

What Models/Analyses are Susceptible to these Deficiencies?

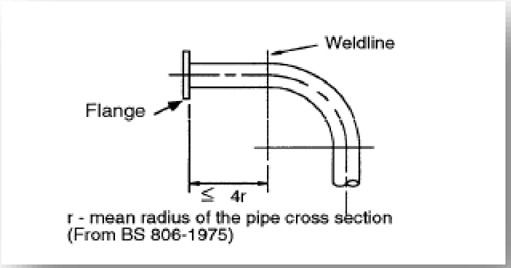
3. Pipe connections to thin walled vessels
   - The flexibility of the connection may be modeled by a flexible element (such as that generated using Welding Research Council Bulletin 297)
   - Stresses in the pipe and vessel may be estimated through the use of FEA or through the use of Welding Research Council Bulletins 107 and 297

What Models/Analyses are Susceptible to these Deficiencies?

4. Highly corrosive systems – especially when subjected to cyclic loadings
   - Corrosion of a pipe results in an irregular cross-section
   - Typical approach is conservative:
     - Un-corroded cross-section is used to generate load and stiffness terms (weight and thermal forces)
     - Fully corroded cross-section is used for calculating section modulus (stress calculation).
   - Corrosion is much more dangerous under fatigue loadings due to the fact that it provides many more opportunities for crack initiation
     - Surprisingly, some piping Codes do not include corrosion in expansion stress range calculations
     - Consider lowering the cyclic factor (f), to reduce allowable stress (rather than increasing calculated Code stress) for a highly corroded material

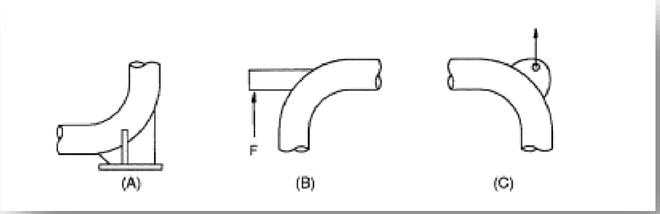
What Models/Analyses are Susceptible to these Deficiencies?

5. Elbows
   - Elbows ovalize significantly when subjected to bending loads. This can be accounted for by increasing the flexibility of the elbow element in the computer model and multiplying the calculated stress by a stress intensification factor (this is in CAESAR II). Code-defined "flexibility factors" for bends have been determined theoretically and verified experimentally
   - Code-defined flexibilities assume at least 2 ODs of straight pipe exist on each side of the bend. Closer components would stiffen the elbow.



What Models/Analyses are Susceptible to these Deficiencies?

5. Elbows (continued)
   - The flexibility and stress intensification factors of bends must be reviewed in those cases where ovalization is inhibited (such as when the elbow is stiffened by flanges or welded attachments). The piping codes provide correction factors for bends with one or two flanges, but do not mention other geometries.
   - The factors for heavily stiffened bends, such as that shown in (A), could be estimated using FEA, or stiffness could be increased by modeling the elbows as flanged, or simply as square corners with SIFs defined. In less pronounced cases such as those shown in (B) and (C), deviation from the response of an unstiffened bend is usually ignored



What Models/Analyses are Susceptible to these Deficiencies?

6. Loadings which produce stresses which are well outside of the code allowable ranges
   - These loads will tend to produce stresses:
     - well beyond the material yield stress
     - stresses in the buckling range
   - Or, produce excessive motion:
     - large displacements resulting in significant P-delta loads, or
     - large rotations (leading to inaccurate results).
   - CAESAR II analysis cannot be considered accurate should loads produce overly large stress, deflection or rotation.
   - However accuracy is not affected for those loads which are of most interest to the engineer as code allowable stresses are based upon the fact that the analysis being done assumes linear material response.

INTERGRAPH

What Models/Analyses are Susceptible to these Deficiencies?

7. Non-linear boundary conditions
   - The effects of non-linear restraints must be simulated through an iterative process aimed at convergence of the non-linear restraints in legitimate states. For example, with the pipe lifted off at a one-way support (and with the support function removed from the analysis), or with the pipe sliding along a frictional restraint (and with an appropriate force applied opposite the line of action in the analysis).
   - This process is activated (during static analysis) automatically when a non-linear effect is included in the model.

What Models/Analyses are Susceptible to these Deficiencies?

8. Non-homogenous elements
   - As noted, piping elements are modeled as stick elements of constant cross-section and material properties.
   - Reducers defined in CAESAR II are internally modeled as a series of elements of uniformly decreasing diameters.
   - Glass- or refractory-lined pipe models should be based on the expected overall strength of the pipe but include the total weight
   - Soil properties change with terrain and burial depth
   - Temperature gradients along the pipe (e.g., the progressive cooling of a hot gas after compression) may be included by adding discrete temperature changes along the run.

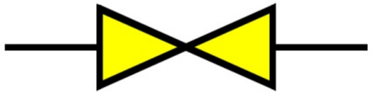
What Models/Analyses are Susceptible to these Deficiencies?

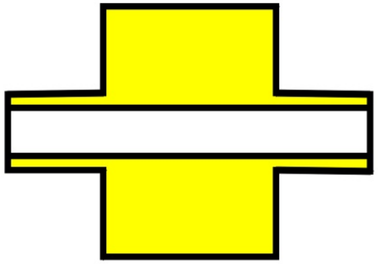
9. Rigid elements
   - Piping components such as valves and flanges are most difficult to model accurately due to the inability to represent their true geometry
   - Program's like CAESAR II are not used to evaluate distortion and stress in such components.
   - The effect of these components can be included in piping system evaluation by providing an element of high relative stiffness in the model. Elements defined as RIGID do this automatically.
   - Additional rigid elements can also be used to model other items such as motorized operators hanging of the valve.

INTERGRAPH

Rigid Element Characteristics

9. Rigid elements (continued)
   - Stiffness based on 10 times wall thickness





- If WEIGHT > 0

  Total Weight =
  specified weight
  + fluid weight
  + 1.75 * insulation weight
  (based on entered OD)
  + refractory weight

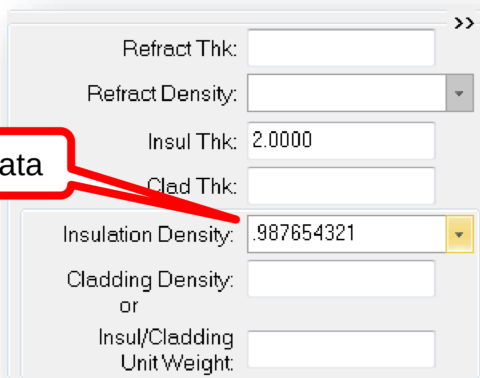
- If WEIGHT = 0

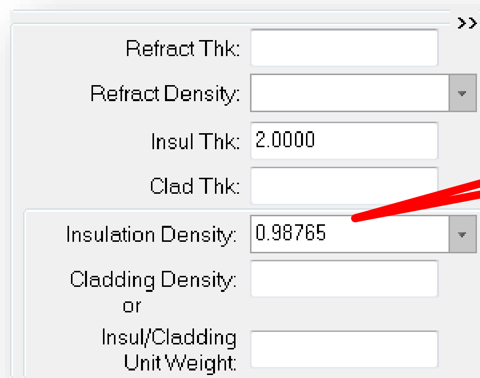
  Total Weight = 0, regardless of any specified fluid, insulation & refractory lining

Data Precision

- CAESAR II is accurate; CAESAR II does not measure, it calculates
- For the most part, precision is set by the input data
  - Nearest ¼ inch, nearest 50 degree F
- Don’t be fooled by the program’s significant digits:
  - Input will display a set number of digits no matter how precise your data:

Entered data

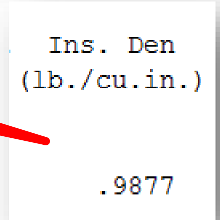


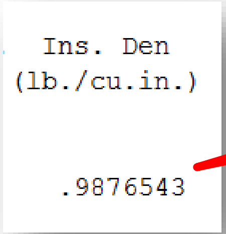


Displayed data

  - Input echo:

Default listing

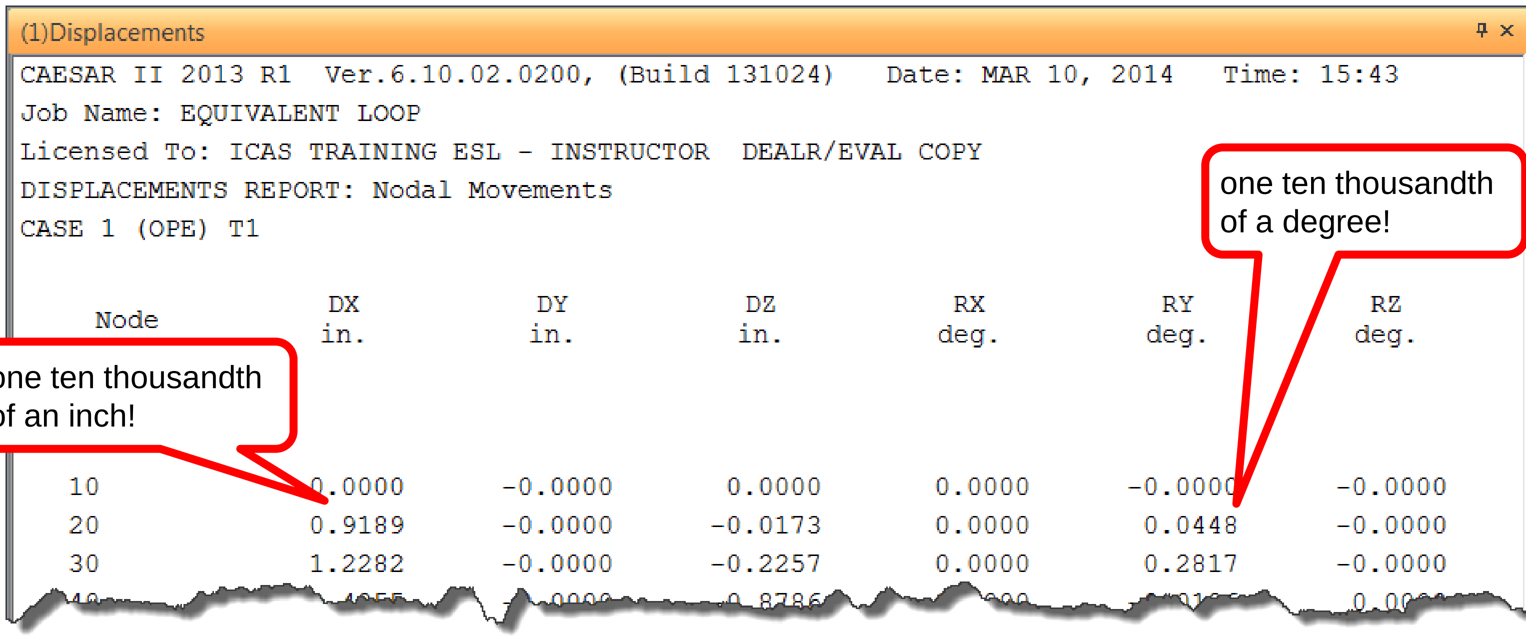




Modified format statement

Data Precision

- Don’t be fooled by the program’s significant digits:
  - Output, too, is a set number of digits



(1)Displacements

CAESAR II 2013 R1 Ver.6.10.02.0200, (Build 131024) Date: MAR 10, 2014 Time: 15:43
Job Name: EQUIVALENT LOOP
Licensed To: ICAS TRAINING ESL - INSTRUCTOR DEALR/EVAL COPY
DISPLACEMENTS REPORT: Nodal Movements
CASE 1 (OPE) T1

Node	DX in.	DY in.	DZ in.	RX deg.	RY deg.	RZ deg.
10	0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0000
20	0.9189	-0.0000	-0.0173	0.0000	0.0448	-0.0000
30	1.2282	-0.0000	-0.2257	0.0000	0.2817	-0.0000

  - You can adjust this display, too, if you wish

Data Precision

- You can use a very tight tolerance in CAESAR II but remember, the pipe fitter may not worry about such things.

Engineering Sensitivity

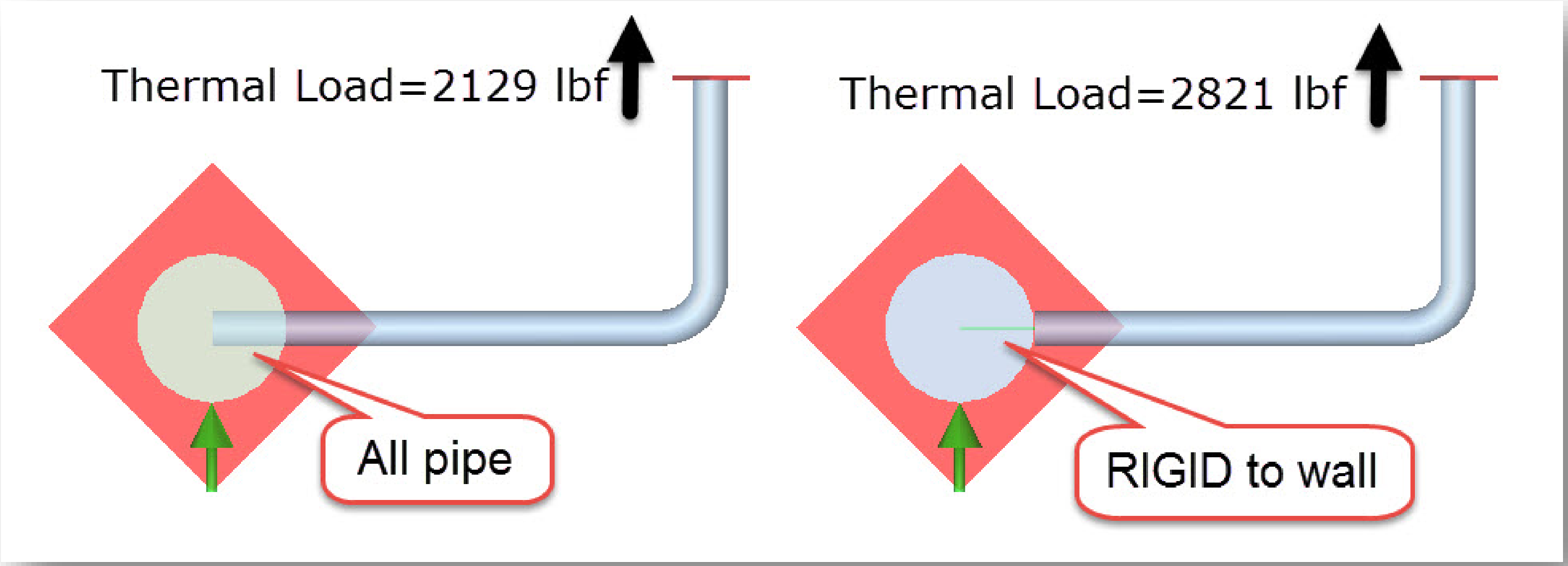
- Evaluating Tolerances
  - Loads (the F in F=KX)
    - Design Conditions versus Operating Conditions
      - Design temperatures and pressures are Code-defined terms to set pipe wall thickness
      - Stress analysis focuses on operating conditions
      - What do you use in CAESAR II?
    - Weight
      - Material densities are typical but they do vary
      - Valve weights in the valve/flange database may vary greatly based on manufacture
    - Fluid weight in risers
      - Fluid density is applied along the pipe axis, no matter the direction
      - The vertical column of fluid is resting on the "pump impeller", it's not stuck to the pipe wall. This extra fluid weight may affect hanger sizing
    - Ambient temperature
      - At what temperature is the pipe cut, at what temperature are the piping components assembled?
      - Is the default ambient temperature of 70F appropriate?

Engineering Sensitivity

- Evaluating Tolerances
  - Loads (the F in F=KX)
    - Wind, wave, and seismic loads
      - Statistics-based values, typically set by (building) codes and standards
      - Difficult to predict a random maximum over time
    - Harmonic loads (pulsation, mechanical vibration)
      - Apparently random forcing frequencies limit analysis of specific events
      - Trend now is to evaluate a system's "likelihood of failure" based on the system's lowest mechanical natural frequency
      - Focus on typical failures – small bore connections – add more strength rather than rely on analysis
      - A system walk down may be more revealing that a computer analysis

Engineering Sensitivity

- Evaluating Tolerances
  - Stiffness (the K in F=KX)
    - Beam stiffness is based on length ($K=3EI/L^2$) but some centerlines are too long
      - Small branches off large OD runs or nozzles of modeled vessels run the branch to the run center, that's too flexible
      - Use rigid elements to construct the branch pipe:



Engineering Sensitivity

- Evaluating Tolerances
  - Stiffness (the K in F=KX)
    - Young's Modulus
      - Moduli of elasticity are typical but they do vary
      - Code says use "reference" modulus (ambient)
      - Hot modulus is an effective way to reduce strain-based load
    - Structural Steel in CAESAR II
      - Structures should be designed to carry load without deflection, but…
      - Structure and piping may interact, this may be more significant in dynamic evaluation
    - Flexibility of branch connections
      - Appendix D provides no flexibility for branch connections
      - All Appendix D values are data based on 4 inch Std, size on size fittings
      - Appendix D warns of known inaccuracies
      - Reduced outlets and thin wall headers do have flexibility
      - Use FEA to build more correct models (e.g. FEATools)

INTERGRAPH

Engineering Sensitivity

- Use a sensitivity study to determine the relative importance of specific model content
- What is a sensitivity study?
  - Treat CAESAR II as a black box.
  - Examine the effects of a single input modification.
  - Determine the sensitivity of the results to that particular piece of data.
  - Examples: nozzle flexibility, friction, support location, restraint stiffness.
- If a particular piece of data impacts the analysis, then the model is sensitive to that data.
  - Be sure to confirm that the change is appropriate.
  - If the change has no impact, such data is insignificant <u>for this model</u>.
- Be sure to keep the level of sophistication consistent throughout the model – e.g., don't model one vessel nozzle as flexible and another as rigid since this will improperly shift load & strain distribution.

Boundary Conditions

- Choice in defining restraints is the greatest cause of different results.
- CAESAR II defaults to 1E12 lbf/in for restraints without a stiffness defined
  - The length of an unguided cantilever for a W44X285 section (the largest in the CAESAR II steel database) required to give a stiffness of 1E12 is 1.3 inches!
- Is ANCHOR or RIGID always conservative?
  - Generally, stiffer is conservative for strain loads but this is not necessarily true for force-based load distribution
- Does the inclusion of structural steel improve the model?
  - Maybe, but this implies that the pipe can move the steel and that is NOT the assumption made by engineers designing the supports
  - Modeling pipe rack would require all pipes on the rack to be modeled together. Models would be most comprehensive but much larger and less dependable.

Boundary Conditions

- Choice in defining restraints is the greatest cause of different results.

- Centerline support vs. actual location
  - Locating the true contact point is important when a restraining load may create a significant bending moment
- Is our pencil too sharp?
  - Some details are just too detailed to be considered
  - A good example is gaps on guides – all guides require some clearance to operate properly but these gaps are not controlled (engineered gaps) and should not automatically be included in the model
- What about modeling soil?
  - Only point supports are included in CASEAR II, continuous support requires many extra closely-spaced supports
  - Stiffness terms for soil are very inexact and vary by location

Modeling Choices

- We abide by piping code requirements and, remember, that the Code is a simplification. Quoting B31.3:
  - 300 General Statements
    (c) Intent of the Code
      (3) "Engineering requirements of this Code, while considered necessary and adequate for safe design, generally employ a simplified approach to the subject."
- Material Specification is a lower bound, material could be stronger
- (B31.3) allowable stress as MINIMUM(2/3 S_{yield}, 1/3 $S_{ultimate}$) implies a large factor of safety. Expected yield in calculation does not match true response
- According to Code, only 2/3 of cut length should be used in evaluating equipment load. Why? B31.3: "The factor two-thirds is based on experience which shows that specified cold spring cannot be fully assured, even with elaborate precautions."

Modeling Choices (continued)

- Friction, use it or not?
  - There is no standard here other than the oft-quoted mu=0.3
  - CAESAR II has a Load Case Option to turn friction on and off, use this to find a range of results
  - Never use friction to your benefit
- “Fully Restrained Pipe” (B31.4, B31.8)
  - The transportation codes segregate piping into two discrete groups each with their own stress calculation
    - Pipe that can develop bending stress with tension
    - Pipe that is locked in compression (fully restrained pipe)
  - There is no guidance on where this transition point occurs in your model

Modeling Choices (continued)

- Hot Modulus of Elasticity vs Cold Modulus
  - Code-defined stress calculations specify the use of E_c (the CAESAR II default) but using E_h for reactions is implied.
  - As with friction, the user can run both conditions in a single analysis by setting Load Case Options.
- Hanger sizing settings
  - Verify and double check system weights if you depend on factory presets (i.e., installed & operating loads)
  - Watch out for additional hardware weights (between spring & pipe) on light springs
  - Include the Actual Installed Load Case in your analysis

Modeling Choices (continued)

- Many engineers avoid hard decisions by using conservative assumptions. This approach must be tempered by the greater cost of the resulting design.
- Analysis versus the Real World -or- Design versus As Built
  - The pipe fitter can easily (if unknowingly,) invalidate your detailed model
  - Small errors in construction may lead to mis-alignment which, in turn, leads to uncertainty in actual loads in the field
  - Settlement can also lead to mis-alignment
- Remember, the piping codes establish requirements for safe operation but code criteria do not cover systems in operation
  - Local yielding in the form of shakedown is an accepted condition in the Codes.
  - Such yielding, at some level, invalidates previous analyses.

Modeling Choices (continued)

- Your job is not to make beautiful CAESAR II models.
- Your job is to quickly confirm system safety and reliability or provide changes to make it so.

- Use or establish company standards so that, in a perfect world, all engineers would reach the same conclusion.

Model Verification

- First look at results should be confirmation of model assumptions
  - Develop a list of questionable assumptions while building the model
  - Correct invalid assumptions before continuing
- Focus on stiffness, boundary conditions and loads
  - If it cannot be defined by F=KX, it is not in your CAESAR II model
  - Boundary conditions (restraints and imposed displacements) suffer the widest range of interpretation and model definition
- Static solutions will always reveal equilibrium – resultant loads equal applied loads; make sure the restraint reports make sense
- Verify key coordinates such as equipment and nozzle locations
- Check plotted deflections, though not to scale, deflected shapes should be sensible.

What We Covered

- Introduction
- The digital model
- What’s missing in our CAESAR II model?
- Model precision and construction tolerances
- Engineering Sensitivity
- Boundary Conditions
- Modeling Choices
- Model Verification

The CAESAR II Piping Model – How Good Is It?

Questions?

Comments?

Ideas?

The CAESAR II Piping Model – How Good Is It?

Thank you