Deformable Spotwelds in LS-DYNA for Impact and NVH Applications

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Outline

- Spotwelding Overview
- Rigid Spotwelds
- Deformable Spotweld Elements and Materials
- Spotwelds Connections using Contact Interface
- Spotweld Failure
- General Guidelines

Spotwelding Overview

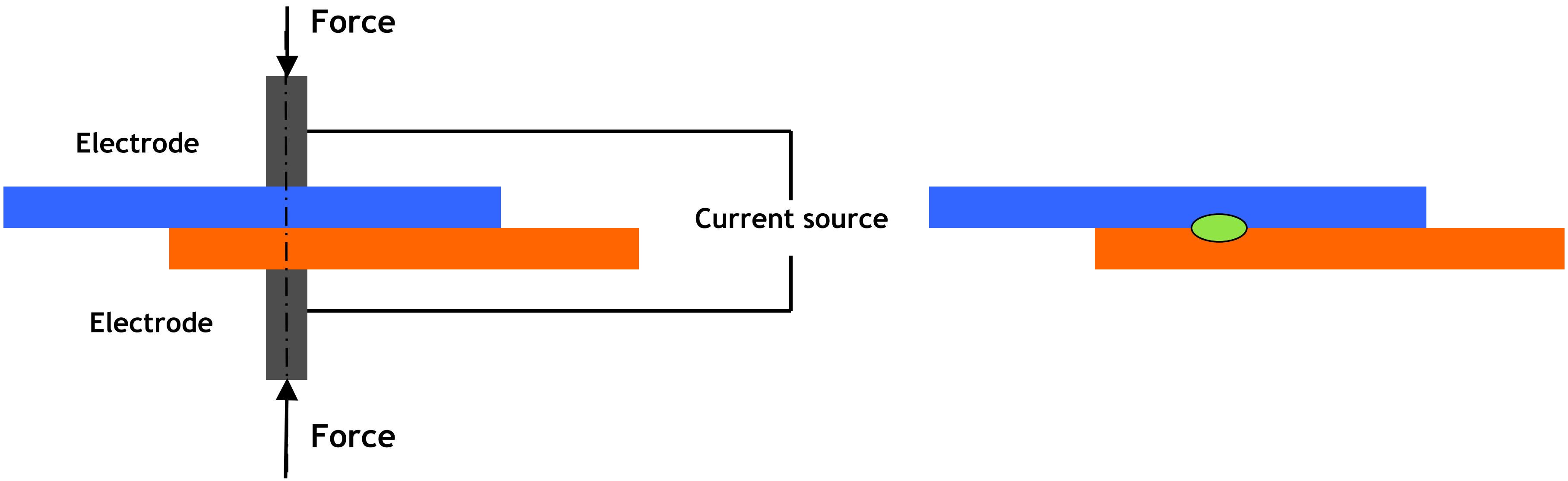
Spotwelding

- Introduction

  - One of the oldest welding processes – in existence for more than a century
  - Used wide range of industries primarily to connect steel sheet bodies
  - As the name suggests, it is used to ‘weld’ parts at a pre-defined ‘spot’
  - Belongs to a category of ‘Resistance’ welding

Spotwelding - Process

- Weld is created using current and force as the primary source
- Current flowing through the metal causes the metal to 'resist' which generates heat
- Heat generated causes the metal to 'fuse' together



Spotwelding - Quality

- Several factors influence the quality of the weld
  - Sheet metal thickness
    - Parts too thin will result in no weld
      - Minimum thickness , 0.5-0.6 mm
    - Parts too thick will result in a weak weld
      - Maximum thickness, 3.0 to 4.0 mm
  - Electrode Force, Weld Current
  - Electrode Diameter
    - Generally the diameter is greater than the desired weld nugget

$$5\sqrt{\min\_sheeet\_metal\_thickness}$$

Spotweld Diameter, Sheet Thickness

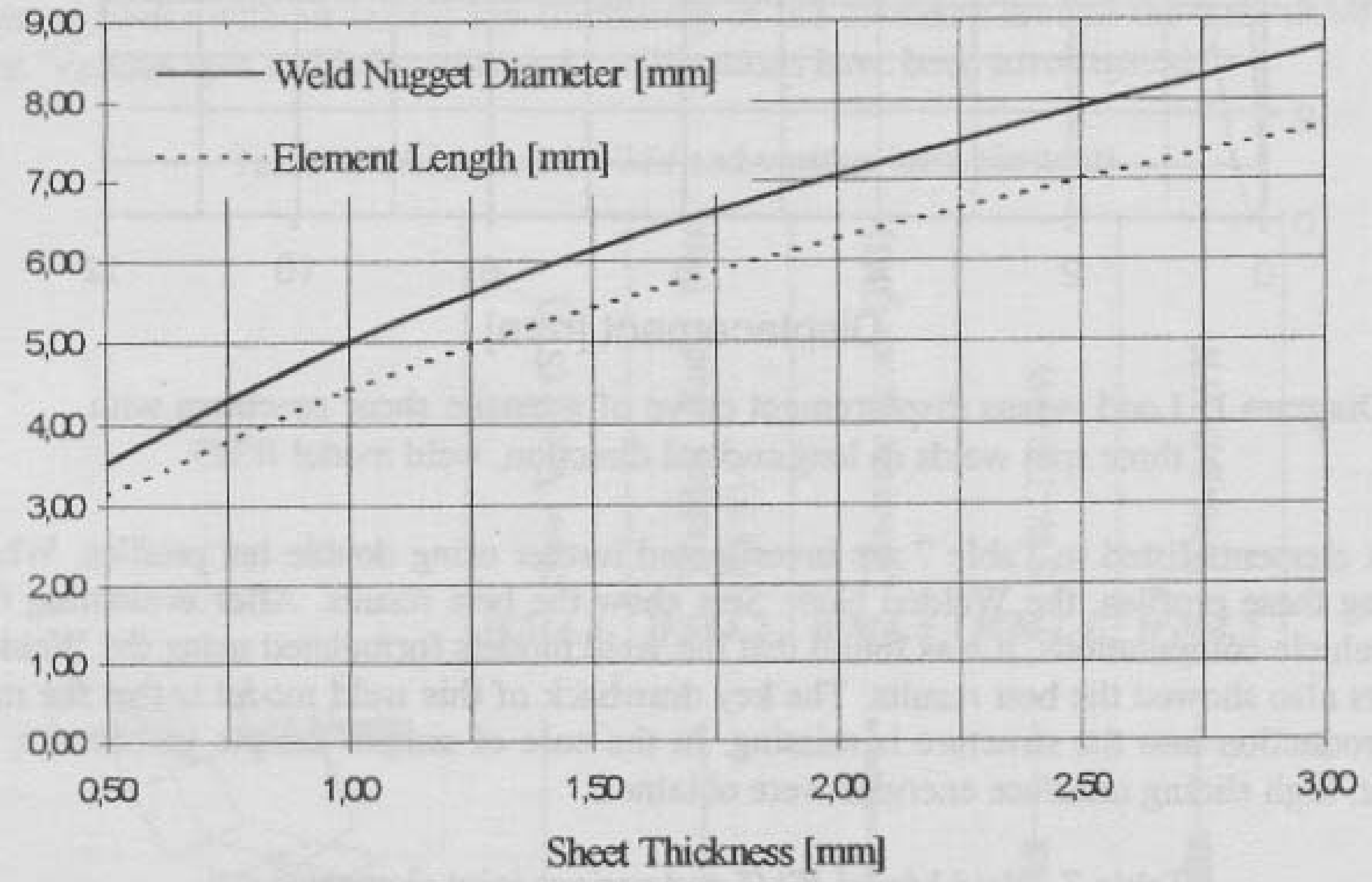


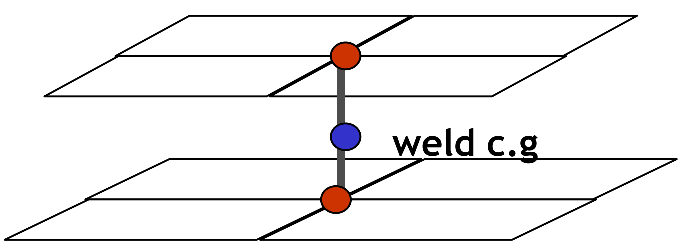
Diagram 2. Dependence of weld nugget diameter and element length on sheet thickness

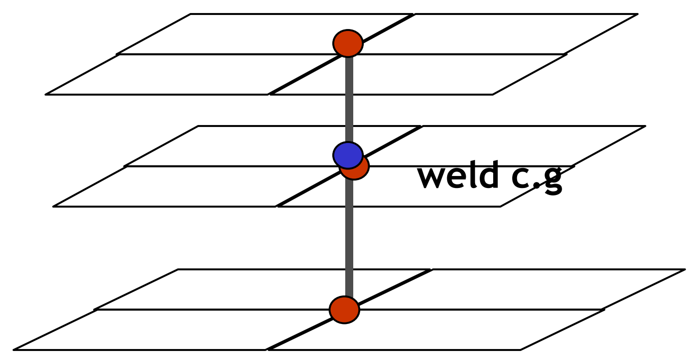
Rigid Spotwelds

Rigid Spotwelds Representation

- In earlier methods, the spotweld was conveniently considered to be a rigid connection between the metal sheets

- Numerically, the connection was represented using rigid-body mechanics
  - Weld Mass = mass of the connecting weld nodes
  - Translation and Rotation degrees of freedom were coupled
  - Weld forces, accelerations were recorded





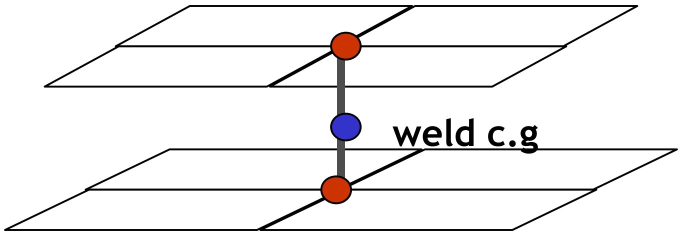
Rigid Spotwelds – Misc Notes

- Weld line must be close to normal to the sheet metal surface

- Weld elements do not control time step
- Failure could be be modeled
  - Brittle
    - Time based, Normal Force and Shear Force
  - Ductile
    - Plastic Strain

Rigid Spotweld - Disadvantages

- Sheet metal mesh must have a matching node at weld projection point

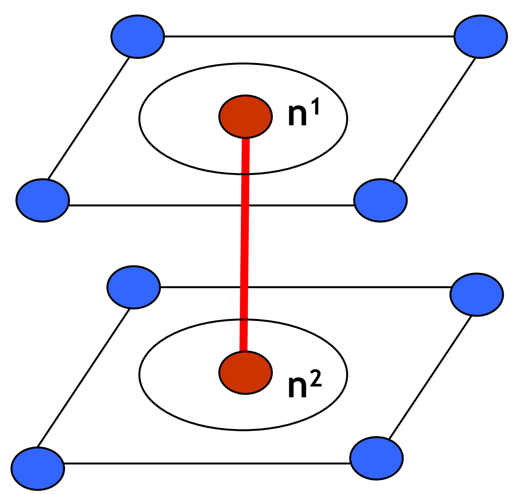


  - Increased pre-processing effort and time
  - Affected mesh orthogonality
  - Weld deformation neglected
  - Usually promoted hourglassing if sheet metal elements used reduced integration

Deformable Spotweld Elements

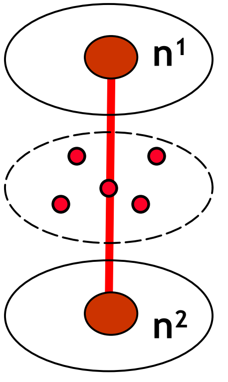
Deformable Spotweld Beam Element (1)

- In 960, LS-DYNA introduced a beam element that could be used for representing spotwelds
  - Circular cross-section using ***SECTION_BEAM**
    - **ELFORM** = 9
    - **CST** = 1, circular
    - Outer Diameter at N1 and N2, **TS1 = TS2**, Weld nugget diameter
    - Inner Diameter at N1 and N2, **TT1 = TT2** = zero



Deformable Spotweld Beam Element (2)

- Some notes of this element
  - Incrementally objective – rigid body rotations do not generate strains
  - Reference axis is between N1 and N2
  - Element variables are integrated
    - mid-point of the reference axis
    - multiple points on the cross-sectional area

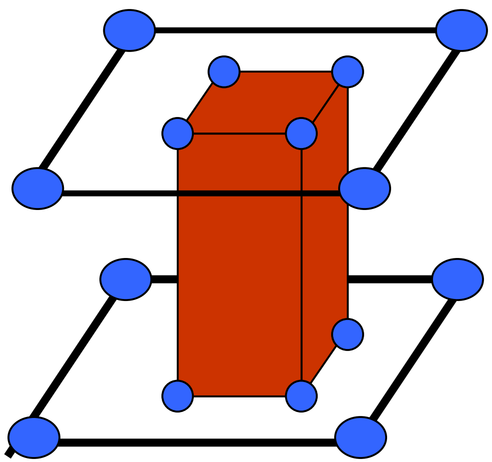


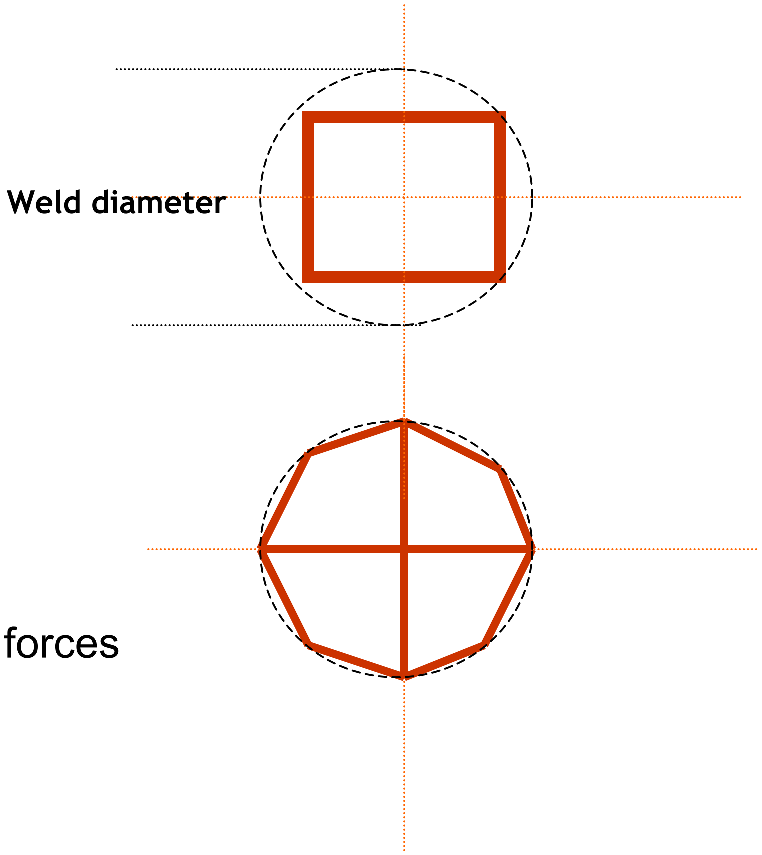
  - Poisson’s effect is ignored
  - Refer theory manual for more information

- Transmitting beam torsional forces requires special treatment
  - Shell has no stiffness about the drilling degree of freedom
  - Treatment should generate in-plane forces

Deformable Spotweld Solid Element (1)

- In 970, the spotwelds can be modeled using 8-noded brick element





- No special treatment to transmit torsional forces

Deformable Spotwelds – Solid Element (2)

- Depending on the sheet metal thickness, the solid element dimensions could be the following

Weld length	Aspect Ratio (Longest Length/Smallest Length)
0.5	10
1	5
2	2.5
3	1.6

- Using a selectively reduced integrated element (elform=2) for bad aspect ratios may result in shear locking and yield excessive stiff behavior

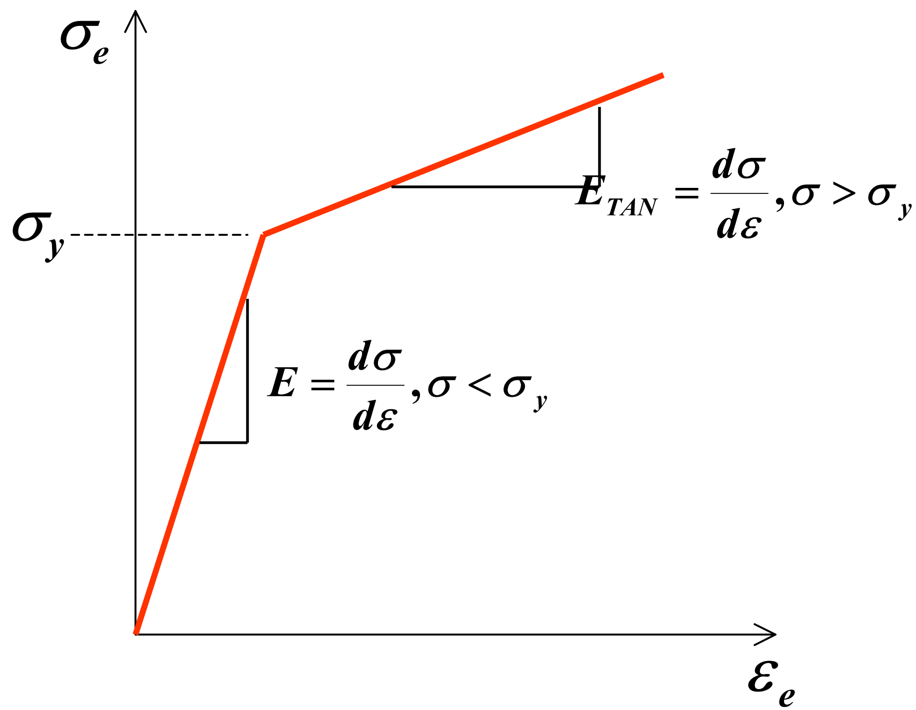
- The recommended element formulation is the under integrated element (elform=1) with appropriate hourglass stabilization method

Deformable Spotwelds – Solid Element (3)

- In LS-DYNA, there are three different types of hourglass stabilization
  - x Viscous – Hourglass types 1,2,3
    - Based on nodal velocities
    - Fails under low-velocities and is more suited for explosive type applications
  - x Stiffness – Hourglass type 4,5
    - Based on element material stiffness
    - Uses QM as a scale factor
    - Results dependent on the user's experience
  - ✓ Assumed strain field – Hourglass type 6
    - It is based on the element geometry and material stiffness
    - With QM=1.0, the elastic beam under pure bending is predicted accurately for very coarse mesh
    - Recommended for spotweld elements
    - Refer paper by Dr. Lee Bindeman

Deformable Elements – Material

- A new material model , MAT_SPOTWELD, was implemented starting v960 to support the constitutive representation of the spotweld material
- The material model is essentially a isotropic bi-linear elastic plastic model with isotropic hardening that includes additional parameters for spotwelds



Deformable Spotwelds - Timestep

- Unlike earlier approaches that used rigid elements, the beam and solid elements control the global solution timestep (explicit analysis only)

- Beam Element

$$\Delta t_c = \frac{L}{c}$$

$$c = \sqrt{\frac{E}{\rho}}$$

- Solid Element

$$\Delta t_c = \frac{L_e}{\left\{\left[Q + \left(Q^2 + c^2\right)^{\frac{1}{2}}\right]\right\}}$$

$$L_e = \frac{v_e}{A_{e\max}}$$

$$c = \sqrt{\frac{E(1-\upsilon)}{(1+\upsilon)(1-2\upsilon)\rho}}$$

Q = function of bulk viscosity

Deformable Spotwelds – Time-Step Scaling

- For explicit analyses, which is conditionally stable, the solution time-step is governed by a single controlling element which has the smallest time-step

- There are two different methods of enforcing a user-defined tidstep
  - Increase the density of the controlling element so as to increase its timestep
  - Decrease the elastic modulus

$$\uparrow \Delta t_c = \frac{L}{c \downarrow} \qquad \downarrow c = \sqrt{\frac{E \downarrow}{\rho \uparrow}}$$

Deformable Spotwelds – Mass-scaling (1)

- For a minimum sheet metal thickness of 0.5 mm, the beam length, with no offsets is equal to 0.5 mm

- Using generic steel property and ignoring Poisson's ratio, the sound wave speed and resulting time-step are

$$c = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{210000 MPa}{7.89e-9 Megagram/mm^3}} = 5159066 mm/\sec$$

$$\Delta t = \frac{L}{c} = \frac{0.5}{5159.067} = 9.69168e-08 \sec onds \approx 0.01 micro \sec onds$$

- Its nearly 100 times lower than we would like it to be which is 1microsecond

Deformable Spotwelds – Mass-scaling - DT

- Besides a global parameter, DT2MS in *CONSTROL_TIMESTEP, to force a constant solution timestep for explicit analysis, we have a local parameter, DT, in *MAT_SPOTWELD that applies only for spotweld elements
  - If DT = 0, abs(DT2MS*TSSFAC) will be used to scale the spotweld mass
  - If DT > 0, DT will be used to scale the spotweld mass
- It is best to set DT=0 if non-zero DT2MS is used
  - LS-DYNA would still report added-mass information for deformable spotwelds

Deformable Spotwelds – Stiffness scaling

- As mentioned previously, the material stiffness of the spotwelds can be decreased to increase the time-step

- To achieve a timestep of 1microsecond for a 0.5mm length weld, the elastic modulus is:

$$E = \frac{L^2 \rho}{\Delta t^2} = \frac{0.5^2 \times 7.89e-9}{1.0e-6^2} = 1972 MPa \approx \frac{1}{100} original\_\mathrm{mod}ulus$$

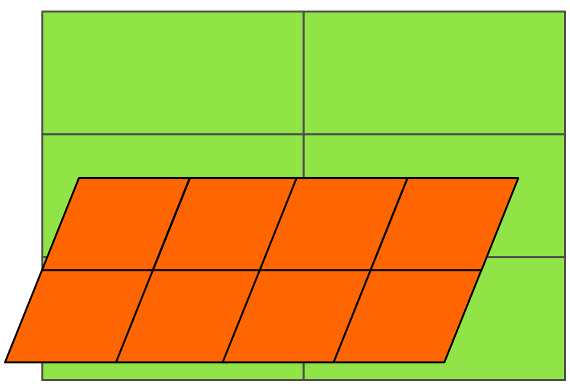
Spotwelds Contacts

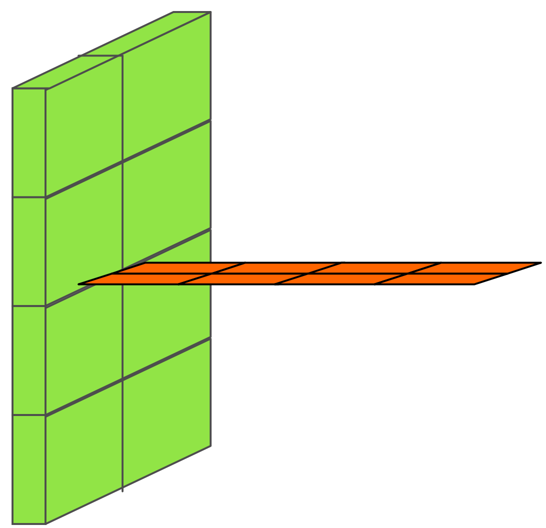
Introduction

- LS-DYNA offers several tied contact to ‘glue’ structures

- It is widely used when arbitrary meshes or incompatible elements are to be merged

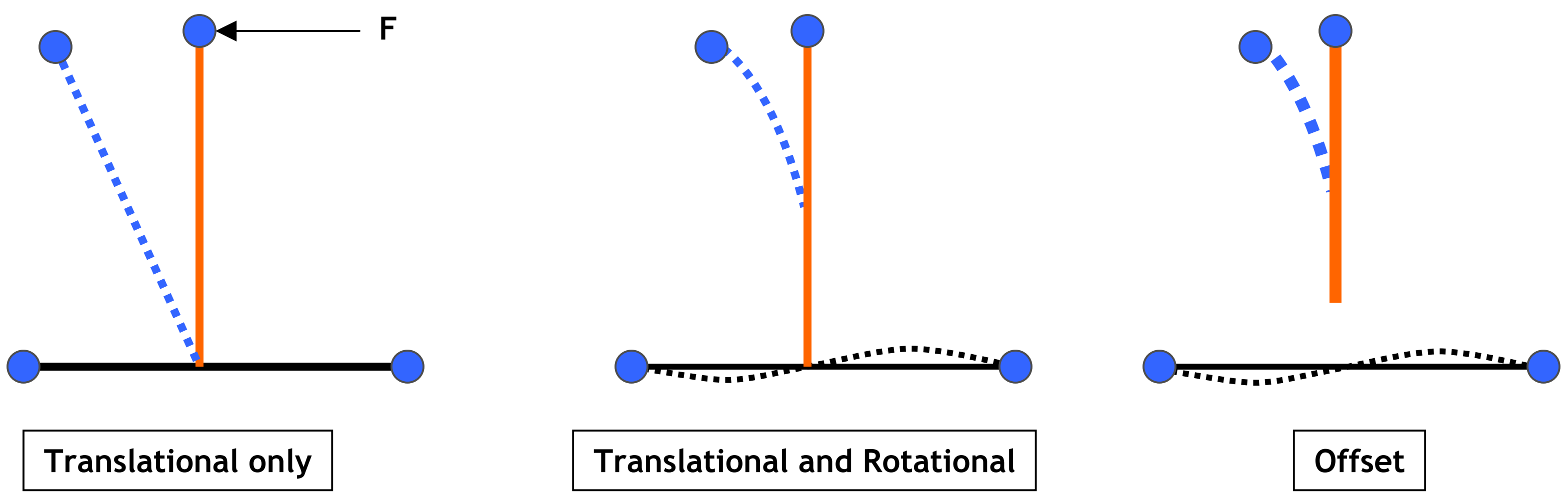
- How does it works ?
  - A constraint based relationship is established between the ‘slave’ and ‘master’
  - As compared with other regular pentalty based contacts, no sliding is allowed with this method





Tied Contact Types

- In LS-DYNA, tied contacts can be broadly classified into following categories
  - Couples only translational degrees of freedom
  - Couples both translational and rotational degrees of freedom
  - Support of Offsets between interfaces

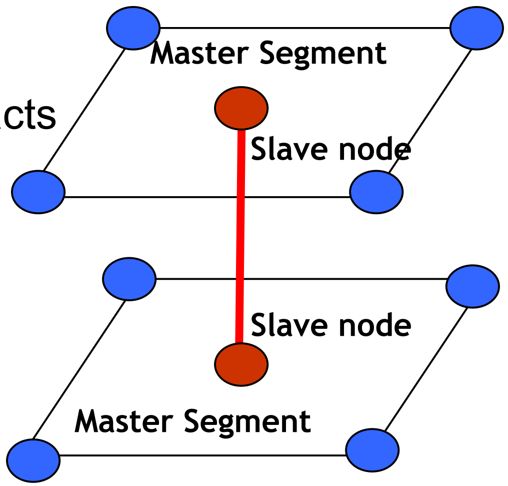


Spotweld Contact

- Unlike several other codes which requires to specify the spotweld to segment constraint explicitly, LS-DYNA offers a contact interface to establish the constraints internally

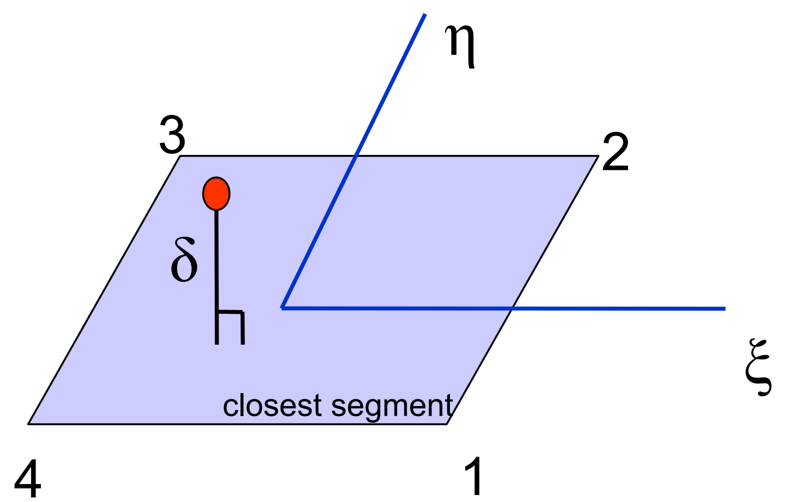
- *CONTACT_TIED_SHELL_EDGE_TO_SURAFCE or *CONTACT_SPOTWELD (v960 and later) is recommended for tying spotwelds
  - Couples both translational and rotational degrees of freedom
  - Spotwelds defined as slave
  - Segments defined as master

- Initialization is performed after other penalty based contacts



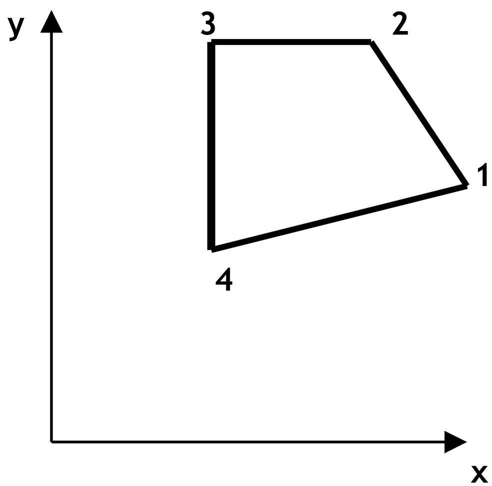
Contact Spotweld Process Overview (1)

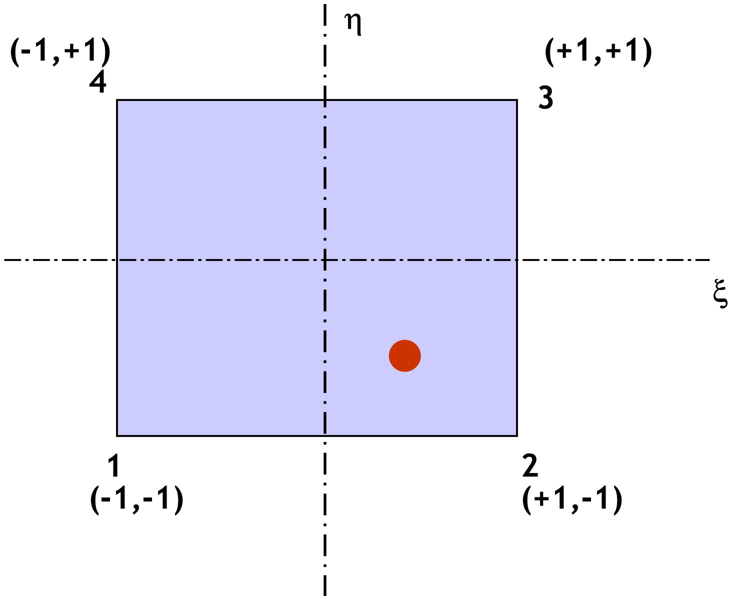
- The tying method is divided into
  - Initialization
    - assemble all slave and master information
  - Segment Determination
    - For every slave node find the closest master segment and establish the contact point



Contact Spotweld - Shape Functions

- Tying method contd.
  - Establish constraints based on shape functions





$$N_1 = \frac{1}{4}(1-\xi)(1-\eta)$$

$$N_2 = \frac{1}{4}(1+\xi)(1+\eta)$$

$$N_3 = \frac{1}{4}(1+\xi)(1+\eta)$$

$$N_4 = \frac{1}{4}(1-\xi)(1+\eta)$$

Contact Spotweld - Constraints

- Tying method contd.
  - Using the shape functions, we can relate the incremental master nodal force and mass using the following equations

$$\Delta f_m^i = \sum_{i=1}^{4} N_i(\xi,\eta) * f_s$$

$$\Delta m_m^i = \sum_{i=1}^{4} N_i(\xi,\eta) * m_s$$

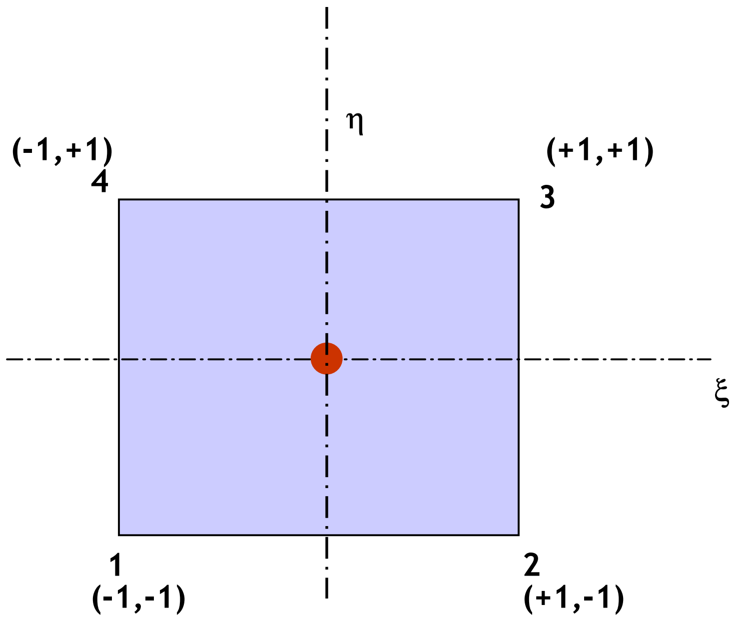
  - Similary, the forces on the slave node can be computed as the weighted average of the master segment nodes

$$f_s = \sum_{j=i}^{4} N(\xi,\eta) f_i^j$$

$$a_{i_s} = \sum_{j=i}^{4} N(\xi,\eta) a_i^j$$

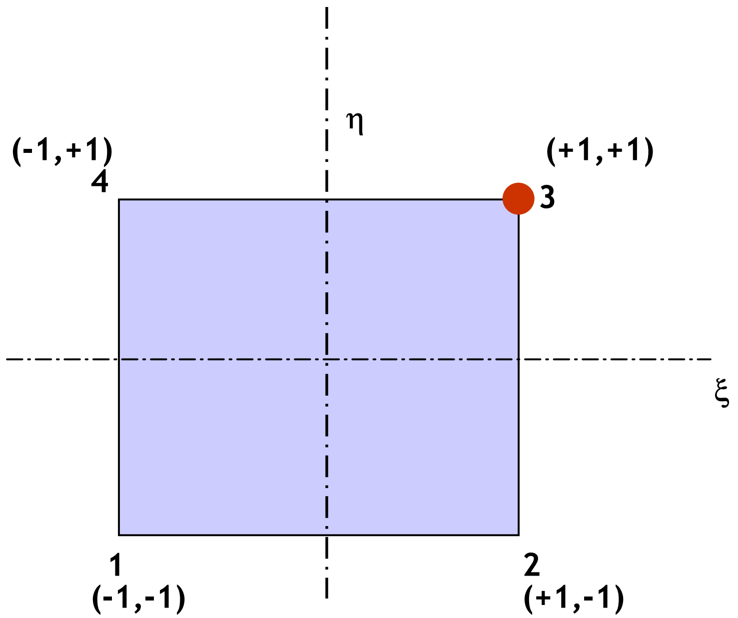
Contact Spotweld – Contact Point at Center

- For a contact point of 0,0:
  - N1=N2=N3=N4=0.25
  - Every master node will get 1/4th of the slave nodal force and mass
  - Larger the area, the ratio is still the same



Contact Process – Contact Point at Node

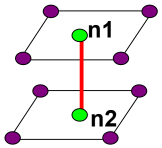
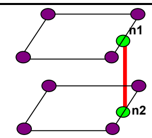
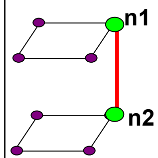
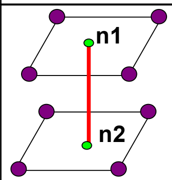
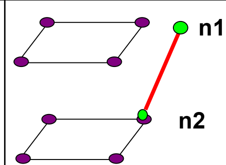
- For a contact point of 1,1:
  - N3=1.0, N1=N2=N4=0.0
  - Only node 3 will get the full slave nodal force and mass while nodes 1,2 and 4 will be zero



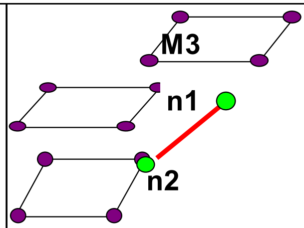
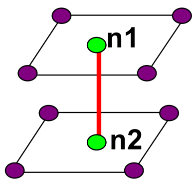
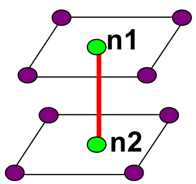
Mesh considerations

- It is imperative that the ideal method to connect the spotweld is
  - meshing the sheet metal to have an element length that is equal to the weld diameter
  - Additionally, to equally distribute the forces to the sheet metal nodes, the weld point should be projected at the center
- However, for relatively small sized mesh the above requirement is not mandatory
- As the sheet metal mesh size increases it is best that the weld point is close to atleast one of the mesh nodes
  - Automatic mesh coarsening

Few Projection Examples

Case	Description	Graphical Representation	Remarks
CASE 1	Beam at Element Centroid		1. n1 and n2 Projected to Master Segment M1 and M2 Respectively 2. Same Forces On All Four Master Segment Nodes
CASE 2	Beam at Element Edge		1. n1 and n2 Projected to Master Segment Edge Nodes 2. Master Segment Edge Nodal Force Dependent On Slave Node Location
CASE 3	Beam at Element Corner Node		Force Equal to Master Segment Corner Node
CASE 4	Beam at Element Centroid Contact Penetration Exists		1. Penetration First Eliminated 2. Projection of Spotweld Nodes 3. Warning Message Printed Indicating Distance Moved
CASE 5	Spotweld Beam In Space (But in Plane of Master Segment)		1. N1 not Projected 2. Warning Message Printed

Few Projection Examples (contd.)

CASE 6	Spotweld Beam In Space (But in Plane of Master Segment) Presence of Another 'Closest' Segment		1. N1 Projected Master Segment M3 2. Warning Message Printed Indicating Distance Moved
CASE 7	Beam at Element Centroid Contact Penetration Exists (S2S)		1. Nodes Not Projected 2. Warning Message Printed Indication Exessive Distortion of Beam
CASE 8	Contact Penetration Exists (S2S) Normals Oriented Outwards		1. Nodes Not Projected 2. Warning Message Printed Indication Exessive Distortion of Beam

Contact Limitations (1)

- When searching for the closest segment, a tolerance is used to determine the criteria for tying

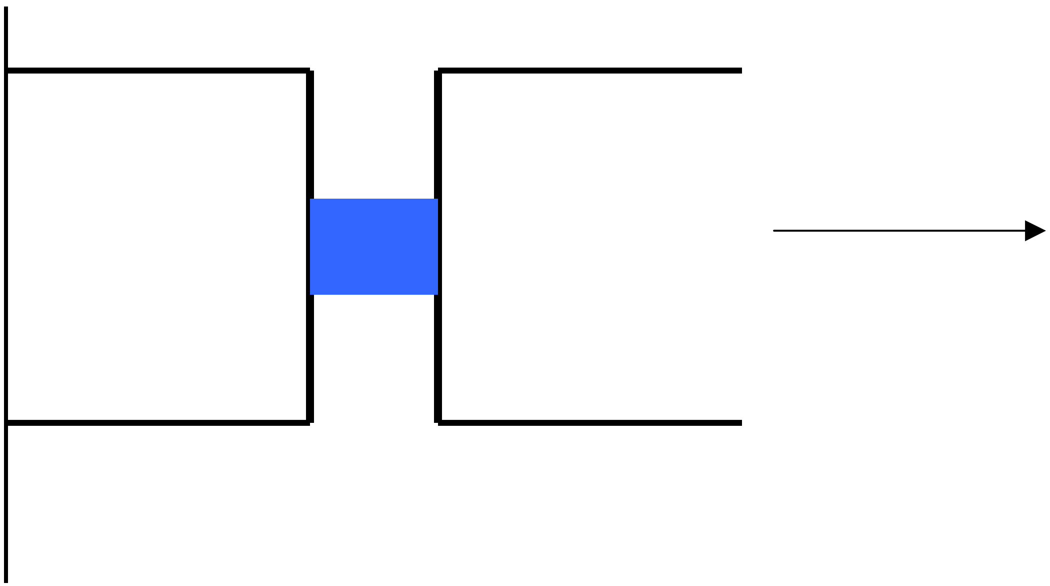
$$\delta_1 = 0.6 * (slave\_thickness + master\_thickness)$$
$$\delta_2 = 0.05 * \min(master\_segment\_diagonal)$$
$$Final\_Tolerance, \delta = \max(\delta_1, \delta_2)$$

  - However, in some instances, the tolerance can be very small so LS-DYNA uses –SST and –MST as variables to overwrite the default tolerances

Contact Limitations (2)

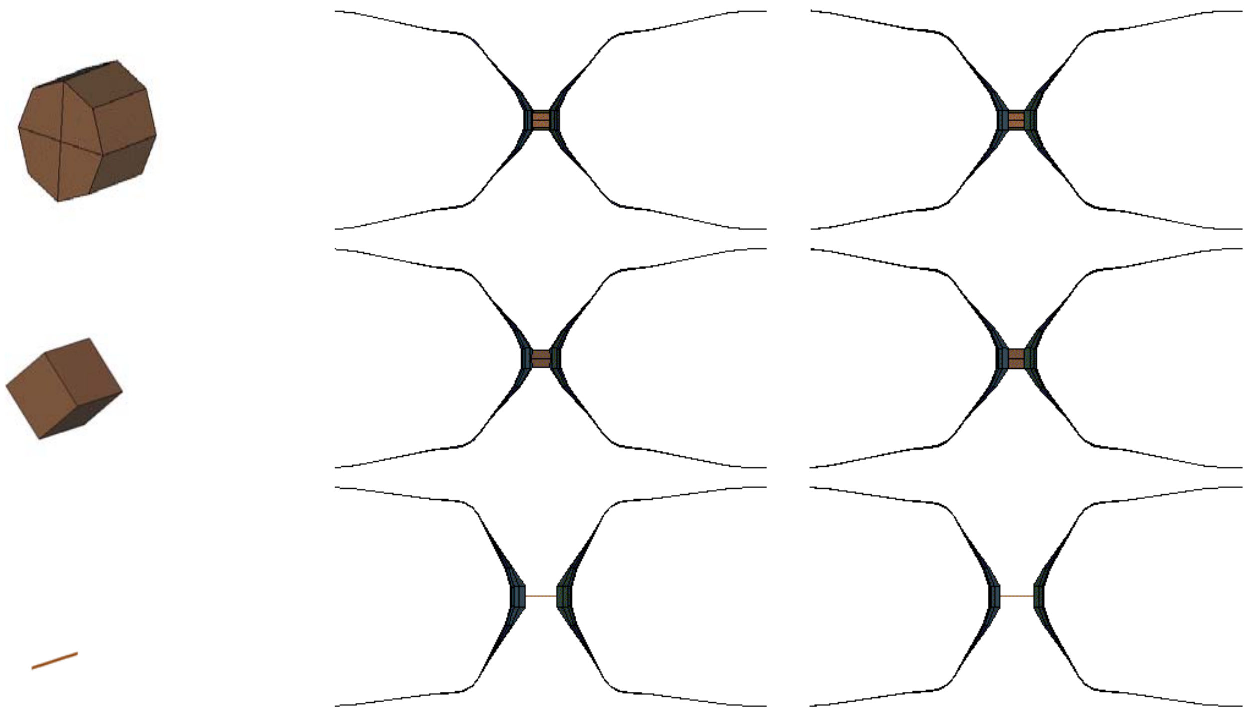
- Since the contact is a constraint based:
  - Multiple slave nodes may be constrained to a single master segment
  - However, the master segment must not belong to any constraints
    - *CONSTRAINED_
    - *MAT_RIGID
  - As an alternative, if the master segment in rigid, the slave spotweld node may be defined as an extra node

Example

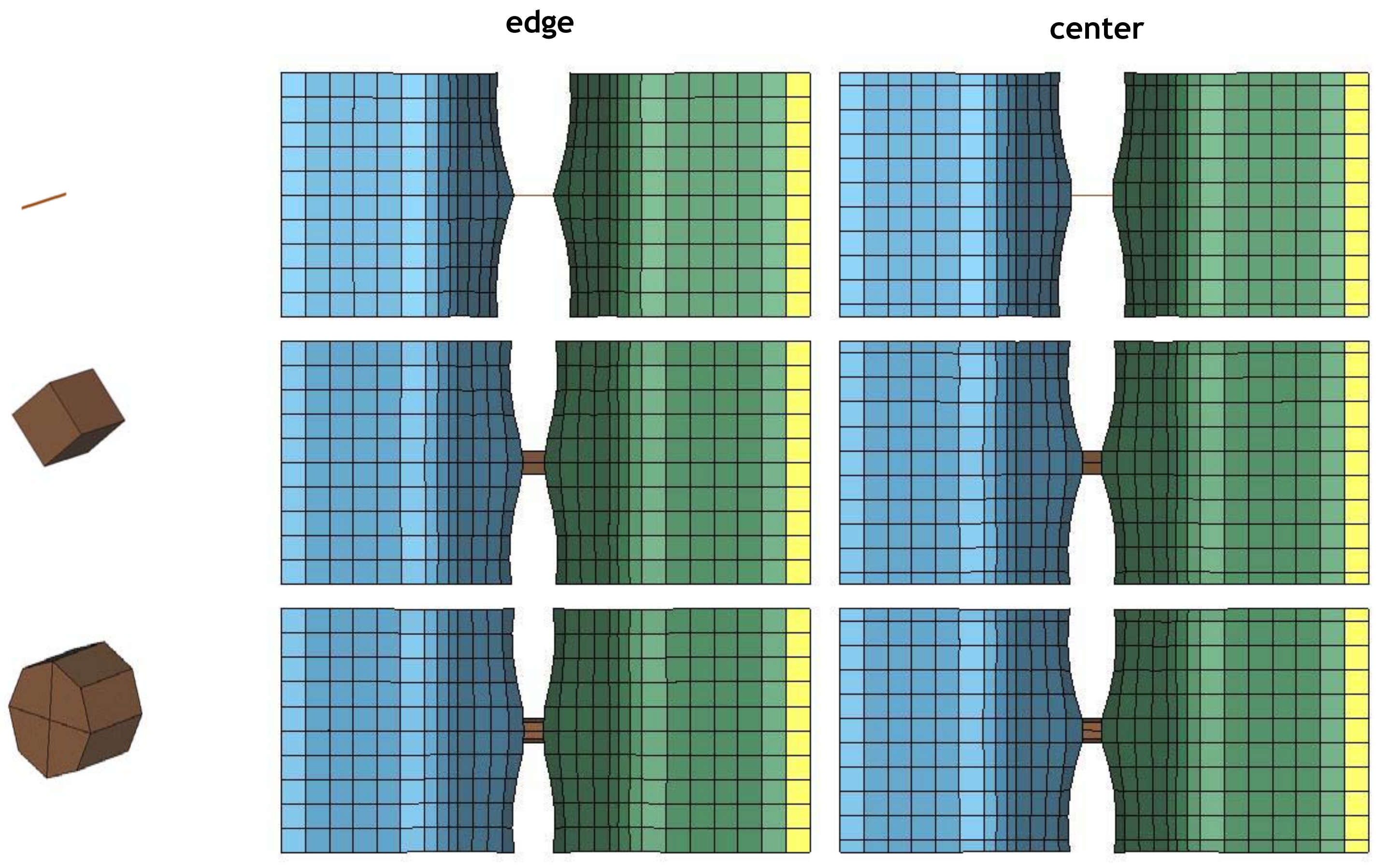


Deformed – Side View

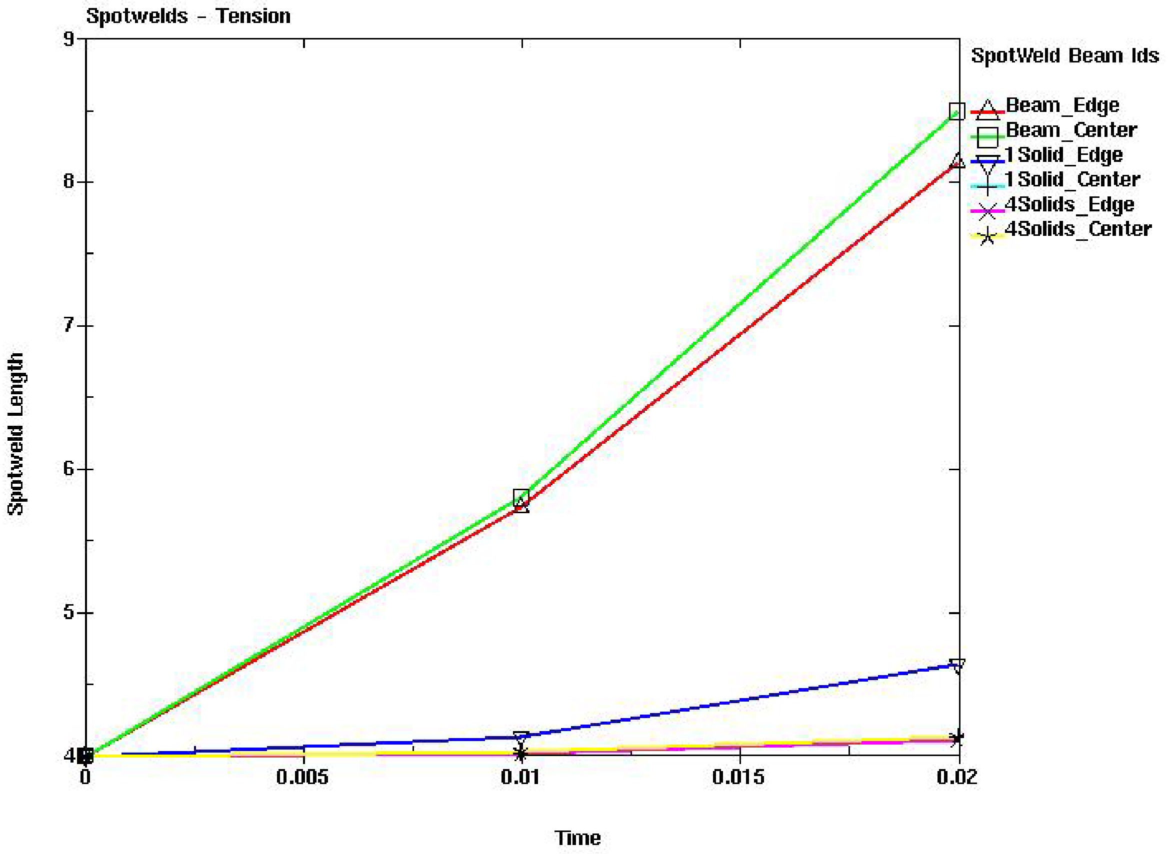
Weld on edge | Weld at center



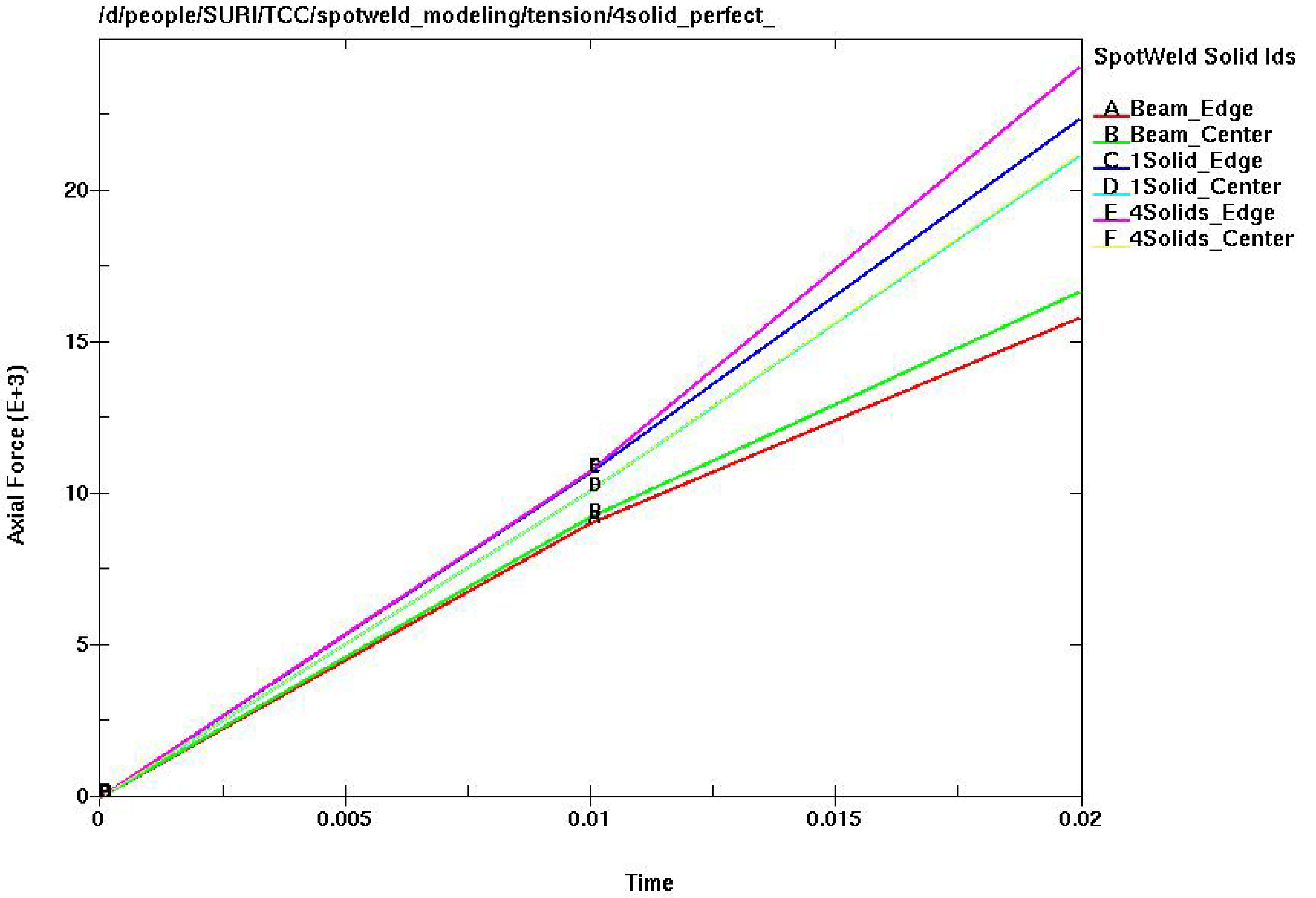
Deformed – Top View



Spotweld Length



Spotweld Force



Spotweld Failure

Introduction

- Several tests indicate that the spotweld or the metal attached to it often fail under extreme loads

- Though the importance to include spotweld failure is understood, a suitable failure theory is difficult to develop without extensive testing
  - DCX is involved with R&D for a large matrix of tests to develop appropriate failure theories

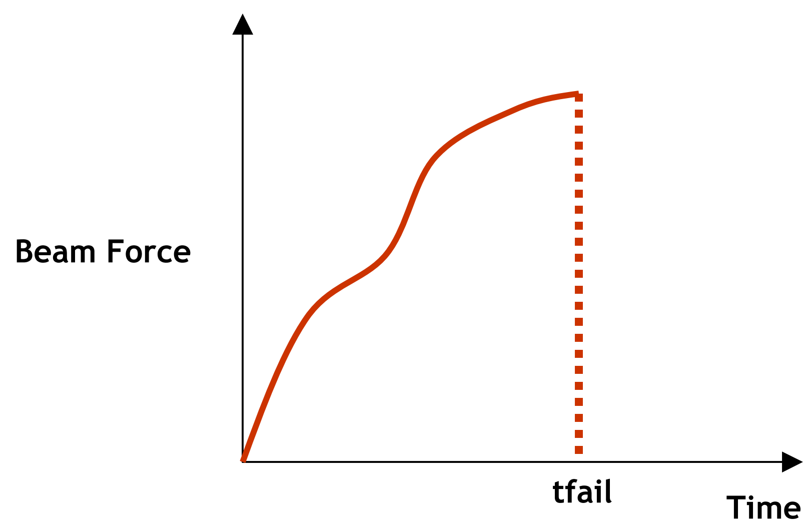
- In LS-DYNA, based on earlier work there are two main failure theories
  - Time based
  - Plastic Strain
  - Resultant Based
  - Peak Axial Stress based on simple beam theory

Time Based Failure

- TFAIL in *MAT_SPOTWELD
  - EQ. 0 – ignored
  - GT. 0 – removes the element from calculation at TFAIL

- Handy when test data exists about weld failure in the model but no other failure criteria exists

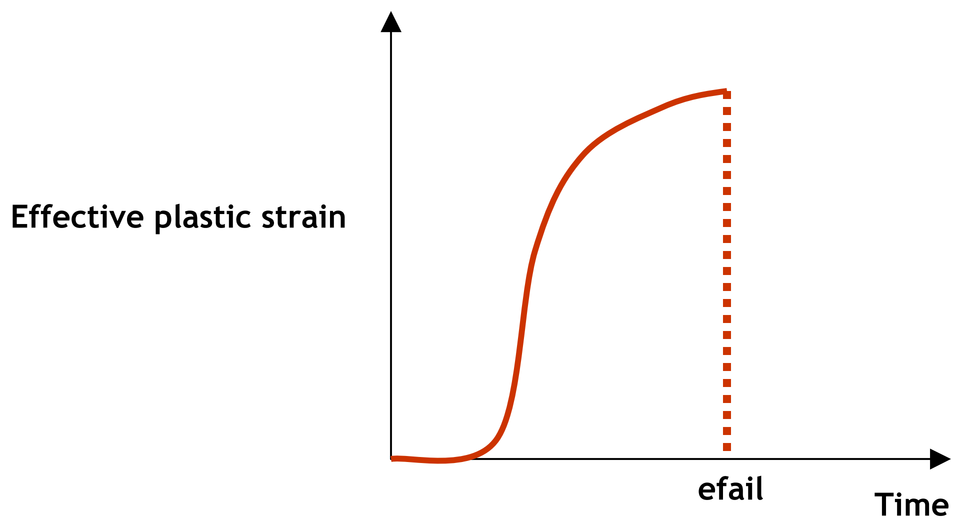
- Brittle Failure



Plastic Strain Based

- EFAIL in *MAT_SPOTWELD
  - EQ. 0 – ignored
  - GT. 0 – failure plastic strain

- Every integration point is checked for this criteria and they fail independently
  - Applies only for beams
  - Entire element is deleted for 8-noded 1-point integration element



Force/Moments Resultants Based

- Spotwelds fail when the resultant variables are outside the failure surface defined by,

$$\left(\frac{|N_{rr}|}{N_{rrF}}\right)^2+\left(\frac{|N_{rs}|}{N_{rsF}}\right)^2+\left(\frac{|N_{rt}|}{N_{rtF}}\right)^2+\left(\frac{|M_{rr}|}{M_{rrF}}\right)^2\left(\frac{|M_{ss}|}{M_{ssF}}\right)^2+\left(\frac{|T_{tt}|}{T_{ttF}}\right)^2-1=1$$

- Considering only Axial Forces:

$$|N_{rr}|=N_{rrF}$$

Simple Beam Theory

- Toyota developed a failure criteria based on simple beam theory

$$\left(\frac{\sigma_{rr}}{\sigma_{rrF}}\right)^2 + \left(\frac{\tau_{rr}}{\tau_{rrF}}\right)^2 - 1 = 0$$

Strain-rate independent

$$\left(\frac{\sigma_{rr}}{\sigma_{rrF}(\dot{\varepsilon}_{ff})}\right)^2 + \left(\frac{\tau_{rr}}{\tau_{rrF}(\dot{\varepsilon}_{ff})}\right)^2 - 1 = 0$$

Strain-rate dependent

$$\sigma_{rr} = longitudinal\_stress = axial\_stress + stress(moments, shear\_stress)$$

$$\sigma_{rr} = \frac{N_{rr}}{A} + \frac{\sqrt{M^2{}_{rs} + M^2{}_{rt}}}{Z} * \tau$$

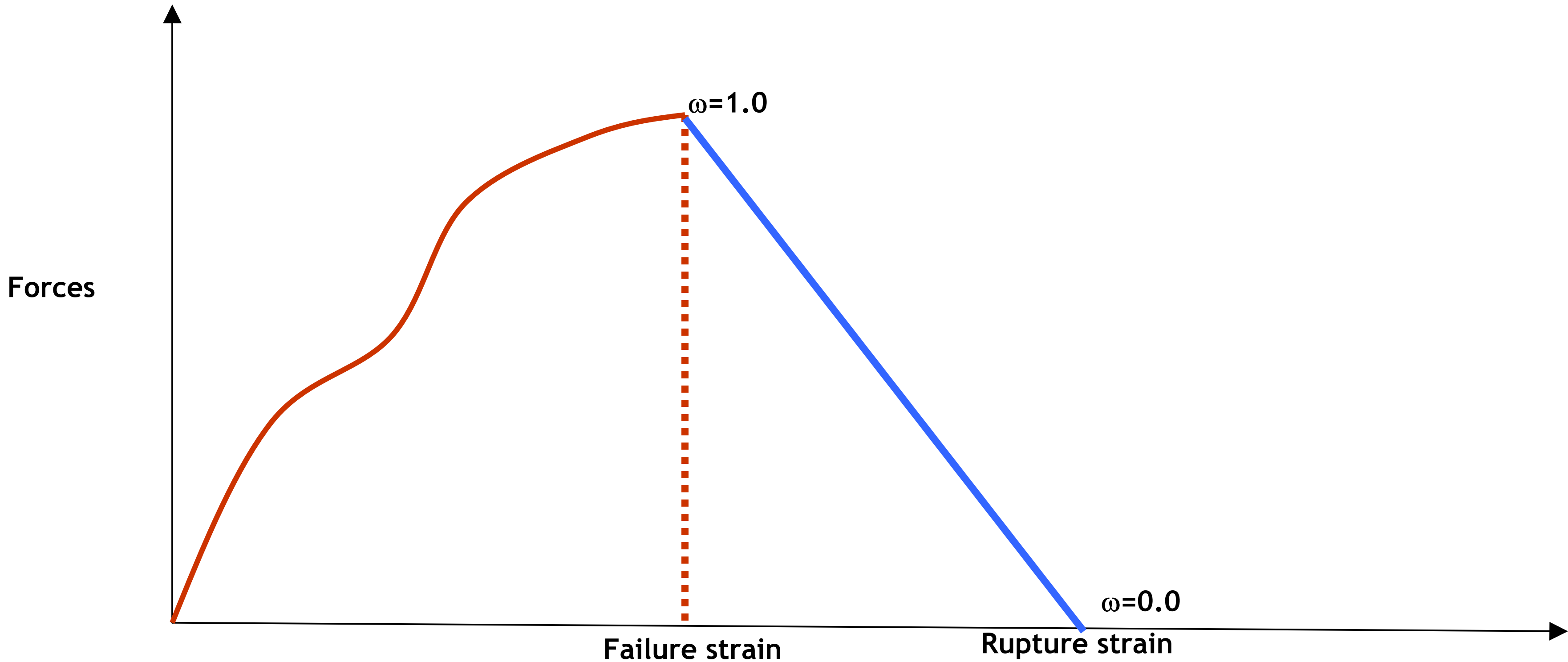
$$A = \frac{\pi * d^2}{4}$$

$$Z = \text{section\_modulus} = \frac{I}{y} = \frac{\pi * d^3}{32}$$

$$d = weld\_nugget\_diameter\ OR \sqrt{\frac{Area\_of\_Brick}{\pi}}$$

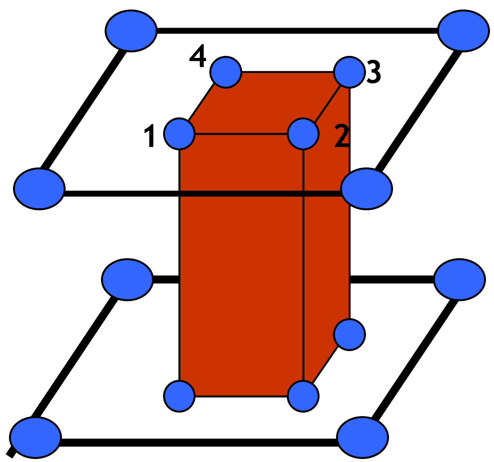
Damage Evolution

- Starting 970, a linear damage evolution parameter is available



Some notes on spotweld failure

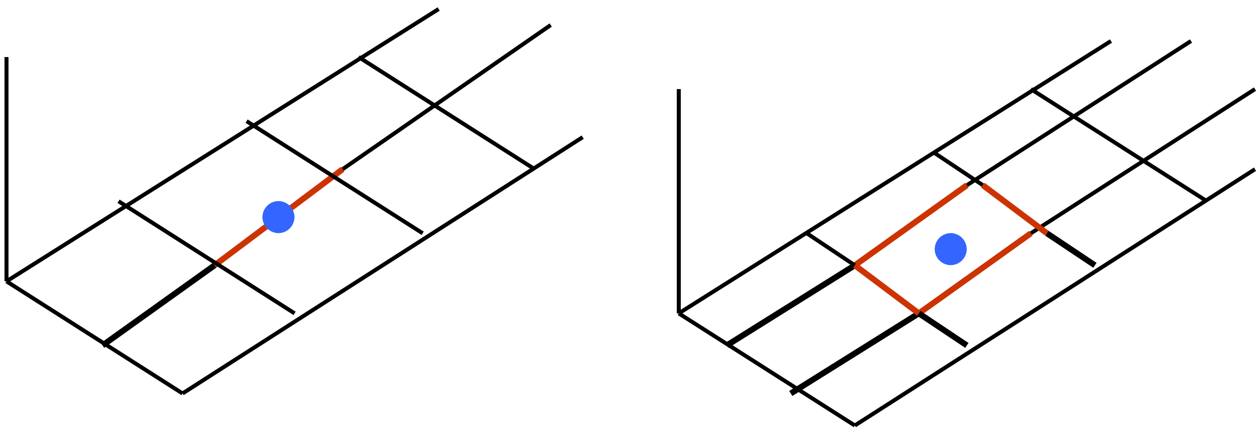
- Spotweld beams seems sensitive to the location of the spotwelded element
- If failure is to be modeled, brick spotwelds are recommended
  - Possible 4 bricks per weld
- NF > 0
  - Number of force vectors for filtering
- Local reference system



General Guidelines – Pre-processing

Preprocessing Guidelines (1)

- Account for sheet metal thickness and weld nugget diameter relationship
- Flanges must be at least 3 elements per side



Preprocessing Guidelines (2)

- Account for all untied spotwelds
  - Special parameters in *CONTROL_CONTACT
    - OUTSEG
      - List of slave nodes and its corresponding master segment
    - SPOTSTP
      - Terminate if a master segment could not be located
    - SPOTDEL
      - If the master segment fails, delete the attached spotweld element

- Use of one single *CONTACT_SPOTWELD contact is recommended
  - Include ALL spotweld PIDs as one slave set
  - Include ALL master PIDs as one master set

- Exclude all spotweld elements from any global sliding contact definitions

Post-Processing Guidelines

Post-processing Guidelines (1)

- If enough care is taken during preprocessing, spotwelds postprocessing is maintenance free

- Request for SWFORC which includes
  - Axial Forces
  - Spotweld Length
  - Shear Force
  - Resultant Force
  - Failure

- Ensure proper mass-scaling was employed
  - Projection of the spotweld node may distort the element

Questions and Answers