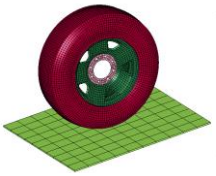
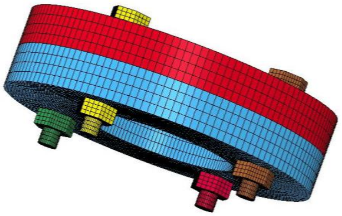
Preload - Introduction

- Sometimes it's important to induce a steady state preload before performing a transient dynamic analysis.
  - Rotating fan or turbine blades, rotating flywheels
  - Gravity
  - Pressure vessels or tires
  - Interference-fit assemblies
  - Stresses induced by a torqued bolt





Preloads in LS-DYNA

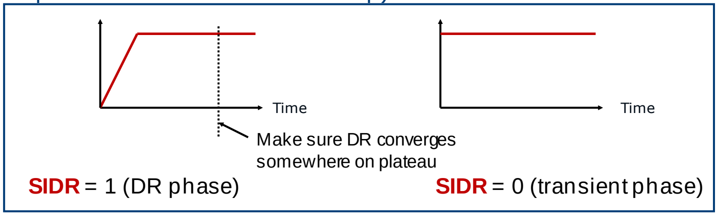
- Preload Analysis Techniques (General)
  - Explicit dynamic relaxation
  - Normal transient analysis with mass damping
  - Implicit methods
    - 2 separate runs: Implicit preload followed by Explicit
    - Implicit/Explicit switching
    - Implicit by *CONTROL_DYNAMIC_RELAXATION
- Specific ways to preload **Bolts**
  - Thermal load
  - Interference contact
  - Initialize stress in solid cross-section
  - Initialize force in beams

Explicit Dynamic Relaxation (DR)

- Explicit **Dynamic Relaxation** is an *optional* transient analysis that takes place in 'pseudo-time' (precedes normal transient analysis).
- DR is typically used to preload a model before onset of transient loading. Preload stresses are typically elastic and displacements are small.
- In explicit DR, the computed nodal velocities are reduced each time step by the **dynamic relaxation factor** (default = .995). Thus the DR solution undergoes a form of damping.
- The **distortional kinetic energy** is monitored. When this energy has been sufficiently reduced, the DR phase terminates and the solution automatically proceeds to the normal transient analysis.
- Alternatively, DR can be terminated at a preset termination time.

Explicit Dynamic Relaxation

- DR is typically invoked by setting the variable **SIDR** to 1 or 2 in *DEFINE_CURVE. This makes the load defined by the curve applicable to the DR phase.
- Curve guidelines
  - Ramp the load during the DR phase and then hold load constant until solution "converges", i.e., until the distortional KE becomes sufficiently small.
  - Maintain the preload in subsequent transient analysis phase (use separate load curve without the ramp)



Explicit Dynamic Relaxation

*CONTROL_DYNAMIC_RELAXATION variables

- **NRCYCK**: Iterations between convergence checks (default=250)
  - Also affects output interval for binary output ***d3drlf***
- **DRTOL**: Convergence tolerance (default=0.001)
  - Ratio of distortional KE at convergence to peak distortional KE
  - Smaller value results in converged solution nearer to steady state but DR solution will take longer
- **DRFCTR**: Dynamic relaxation factor (default=0.995)
  - Scaling factor for nodal velocities each time step
  - If value is too small, model may never reach steady state due to overdamping
- **DRTERM**: Optional termination time for DR
  - DR will stop when time reaches DRTERM even if DR solution is not converged
- **TSSFDR**: Time step scale factor used during DR; can be different than TSSFAC used for normal transient phase.

*CONTROL_DYNAMIC_RELAXATION parameters cont'd

- **IDRFLG**
  - EQ.-999: DR not activated. Overrides **SIDR** in *DEFINE_CURVE.
  - EQ.0: Explicit DR not activated unless by **SIDR** in *DEFINE_CURVE
  - EQ.1: Explicit dynamic relaxation activated with convergence test based on distortional KE of **all parts**
  - EQ.3: Explicit dynamic relaxation activated with convergence test based only on distortional KE of parts in part set **DRPSET**
  - EQ.2: Invokes a completely different and faster initialization approach … **Initialization by Prescribed Geometry** (see next slide)

*CONTROL_DYNAMIC_RELAXATION parameters cont'd

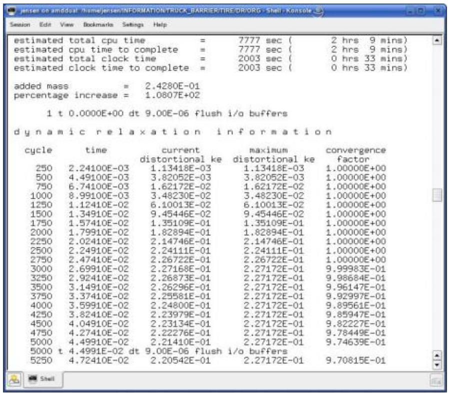
- **IDRFLG**
  - EQ.2: Invokes a completely different and faster initialization approach … **Initialization by Prescribed Geometry**
    - Requires a supplemental input file containing the nodal displacements and rotations corresponding to the preloaded state.
      - Such a file ***drdisp.sif*** is produced by LS-DYNA at the conclusion of a standard DR run .
      - LS-PrePost can also produce this file via Output button, but it won't include the nodal rotations required of beams and shells.
      - Must include "m=drdisp.sif" on execution line.
    - When IDRFLG=2, LS-DYNA runs a precursor explicit analysis, ramping linearly to the specified nodal displacements and rotations in **NC** time steps (default=100 time steps).

Output Related to Dynamic Relaxation

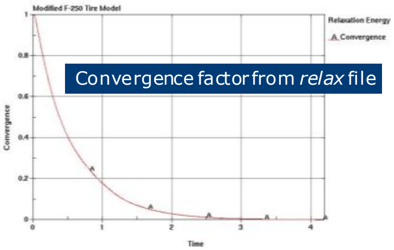
- ASCII output files are <u>NOT</u> written during DR phase, e.g., *glstat*, *matsum*, *rcforc*, etc.
- Time history data of specified nodes and elements (*DATABASE_HISTORY_*option*) are written to binary ***d3thdt*** (*DATABASE_BINARY_D3THDT) if **IDRFLG**=-1
- Binary database ***d3drlf*** is written by including command *DATABASE_BINARY_D3DRLF. If output interval set to 1, then a plot state is written to ***d3drlf*** whenever convergence is checked during explicit DR
  - ***d3drlf*** is to explicit DR phase what ***d3plot*** is to normal transient phase
- ASCII ***relax*** file, containing time histories of distortional KE and convergence factor, is produced by default. Data can be plotted using LS-PrePost.
- At the conclusion of DR, ***d3dump01*** and ***drdisp.sif*** are written. The latter contains nodal displacements and rotations.

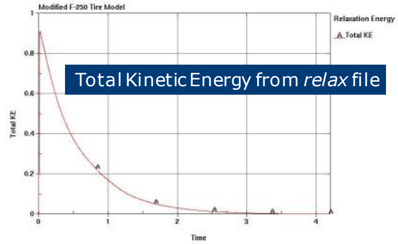
Output - Explicit Dynamic Relaxation

DR information is written to the screen. The normal transient phase starts when the convergence tolerance or a specified termination time for DR is reached.



```
estimated total cpu time          =     7777 sec (      2 hrs  9 mins)
estimated cpu time to complete    =     7777 sec (      2 hrs  9 mins)
estimated total clock time        =     2003 sec (      0 hrs 33 mins)
estimated clock time to complete  =     2003 sec (      0 hrs 33 mins)

added mass           =   2.4280E-01
percentage increase =   1.0807E+02

      1 t 0.0000E+00 dt 9.00E-06 flush i/o buffers

d y n a m i c   r e l a x a t i o n   i n f o r m a t i o n

  cycle       time          current          maximum        convergence
                        distortional ke  distortional ke      factor
    250   2.24100E-03    1.13418E-03      1.13418E-03     1.00000E+00
    500   4.49100E-03    3.82052E-03      3.82052E-03     1.00000E+00
    750   6.74100E-03    1.62172E-02      1.62172E-02     1.00000E+00
   1000   8.99100E-03    3.48230E-02      3.48230E-02     1.00000E+00
   1250   1.12410E-02    6.10013E-02      6.10013E-02     1.00000E+00
   1500   1.34910E-02    9.45446E-02      9.45446E-02     1.00000E+00
   1750   1.57410E-02    1.35109E-01      1.35109E-01     1.00000E+00
   2000   1.79910E-02    1.82894E-01      1.82894E-01     1.00000E+00
   2250   2.02410E-02    2.14746E-01      2.14746E-01     1.00000E+00
   2500   2.24910E-02    2.24111E-01      2.24111E-01     1.00000E+00
   2750   2.47410E-02    2.26722E-01      2.26722E-01     1.00000E+00
   3000   2.69910E-02    2.27168E-01      2.27172E-01     9.99983E-01
   3250   2.92410E-02    2.26873E-01      2.27172E-01     9.98684E-01
   3500   3.14910E-02    2.26296E-01      2.27172E-01     9.96147E-01
   3750   3.37410E-02    2.25581E-01      2.27172E-01     9.92997E-01
   4000   3.59910E-02    2.24800E-01      2.27172E-01     9.89561E-01
   4250   3.82410E-02    2.23979E-01      2.27172E-01     9.85947E-01
   4500   4.04910E-02    2.23134E-01      2.27172E-01     9.82227E-01
   4750   4.27410E-02    2.22276E-01      2.27172E-01     9.78449E-01
   5000   4.49910E-02    2.21410E-01      2.27172E-01     9.74639E-01
   5000 t 4.4991E-02 dt 9.00E-06 flush i/o buffers
   5250   4.72410E-02    2.20542E-01      2.27172E-01     9.70815E-01
```





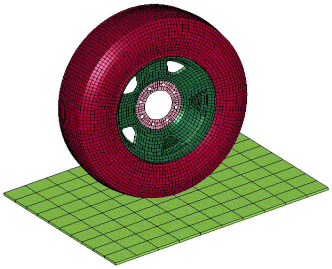
Loads during Dynamic Relaxation

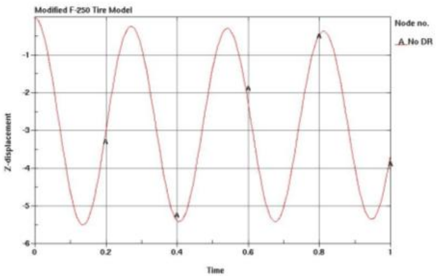
- Gravity loads and centrifugal loads (spinning bodies) are imposed using *LOAD_BODY_*option*.
  - **LCID** and **LCIDDR** are separate curves for normal transient phase and DR phase, respectively.
- Temperatures are prescribed using *LOAD_THERMAL_*option*.
  - Parts, e.g., bolts, defined with a coefficient of thermal expansion will respond to the temperature
  - **LCID** and **LCIDDR** in *LOAD_THERMAL_LOAD_CURVE are separate curves of temperature for normal transient phase and DR phase, resp.
- Other load types or boundary conditions can also be applied during DR if **SIDR** in corresponding *DEFINE_CURVE is set to 1 or 2. Example: *LOAD_SEGMENT, *BOUNDARY_PRESCRIBED_MOTION_*option*.
- *CONTACT_…_INTERFERENCE imposes forces associated with geometric interference, as in a press-fit assembly.
- *INITIAL_… (more on that later)

Explicit Dynamic Relaxation

Example – Gravity Loading on a Tire

Consider a tire with a constant gravity load. **Without DR**, the tire bounces during the simulation as seen when plotting the Z-displacement for a node on the tire rim. Now see the case with DR on the next slide.

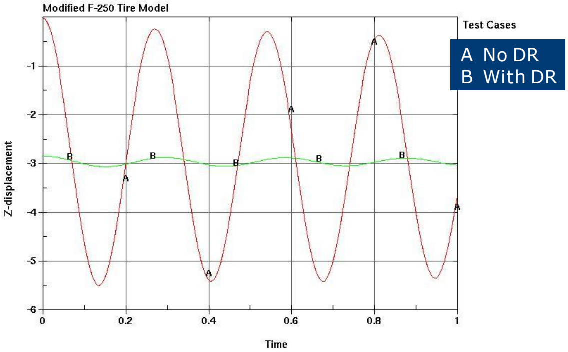




Dynamic Relaxation

Example – Gravity Loading on a Tire (cont'd)

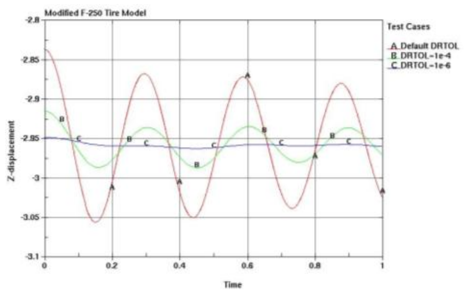
- DR was then included with a ramped gravity curve for the DR phase, i.e., load curve **LCIDDR** (*LOAD_BODY_Z) has **SIDR** (*DEFINE_CURVE) set to 1. The ramp time covers approximately 2000 time steps. The *CONTROL_DYNAMIC_RELAXATION parameters are all set to default. The response during the normal transient phase following the DR phase is shown in curve B below.



Dynamic Relaxation

Example – Gravity Loading on a Tire (con'td)

- Three different settings of the energy convergence tolerance, **DRTOL**, were then tried: 1e-3 (default), 1e-4 and 1e-6. This tolerance is the only change in the model.



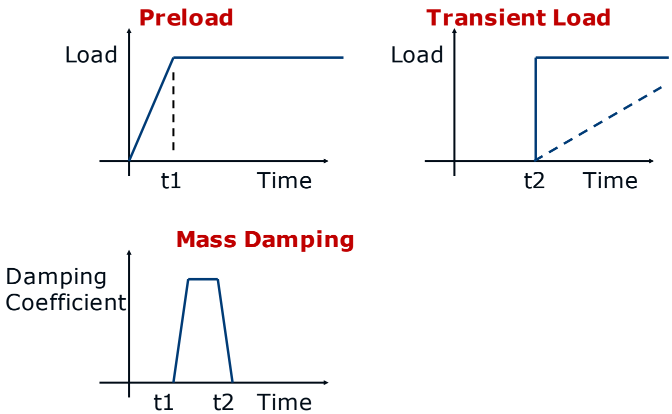
- The value of **DRTOL** offers a tradeoff between run time and amplitude of residual dynamic oscillation.

DRTOL	**1e-3**	**1e-4**	**1e-6**
Elapsed Time (sec)	**3808**	**5032**	**13755**

Preload during Normal Transient Analysis

- As an *alternative* to using DR, in some cases the preload can be established in the early part of a normal transient analysis.
  - Ramp up preload over a finite time and then hold load steady.
  - Use time-dependent mass damping (*DAMPING_GLOBAL with a curve) to inhibit dynamic response during preloading.
    - Drop damping constant to zero after a near steady state preload solution is established and transient loading is ready to be applied.
  - Apply transient loads AFTER preload is established.
    - Use *INITIAL_VELOCITY_GENERATION_START_TIME for problems whose transient response is driven by initial velocityin order to delay onset of "initial" velocity until after the preload is established.
    - Use nonzero birthtime or nonzero arrival time for transient loads

Preload during Normal Transient Analysis



Preload via Implicit Analysis

- In general**, implicit static** and quasi-static, **implicit dynamic** analyses are well-suited to inducing preload. The latter will tolerate rigid body modes and is less likely to encounter difficulty in attaining convergence.
- Implicit analysis requires the command *CONTROL_IMPLICIT_GENERAL
- Other implicit-related commands commonly used are:
  - *CONTROL_IMPLICIT_AUTO automatically adjusts step size based on ease or difficulty in achieving convergence
  - *CONTROL_IMPLICIT_DYNAMICS is used to make the implicit solution dynamic rather than static

Preload via Implicit Analysis

- **Approach 1**: Make 2 separate runs; preload run followed by transient run
  - Make an implicit run applying only the preload. Include *INTERFACE_SPRINGBACK_LSDYNA in the input. This creates an ASCII file called ***dynain*** when the simulation is finished. The ***dynain*** file contains keyword commands describing the preloaded state in terms of deformed geometry, stresses, and plastic strains. Merge these commands into a copy of the original input deck, deselect the implicit cards, incorporate the transient loading, and use this deck to run a second simulation (explicit) that effectively starts from the preloaded state.
    - The *dynain* file does not include contact forces nor does it contain nodal velocities. Thus these quantities from the preload analysis do not carry over to the second analysis.
    - Using data from the last state of the first run's *d3plot*, LS-PrePost® can output a *dynain* file via Output > Format: Dynain Ascii > Write.

Preload via Implicit Analysis

- **Approach 2**: Single run employing implicit/explicit switching
  - Use one input deck where switching between implicit and explicit solvers is determined by a curve.
  - The abscissa of the curve is time and the ordinate is set to 1.0 for implicit and to 0.0 for explicit (curve is a step function).
  - This switching is activated by setting **IMFLAG** in *CONTROL_IMPLICIT_GENERAL to -|curve ID|. Switching from one analysis to the other is seamless and has no CPU or I/O overhead.
  - The objective is to apply the preload using the implicit solver and then switch to explicit on-the-fly to begin the transient solution.

Preload via Implicit Analysis

- **Approach 3**: Single run featuring implicit by *CONTROL_DYNAMIC_RELAXATION
  - **IDRFLG**=5 or 6 activates precursor implicit solution to achieve preloaded state.
    - Only part set **DRPSET** is active during implicit phase if **IDRFLG**=6
  - Set **DRTERM** to termination time of implicit preload solution.
  - *CONTROL_IMPLICIT_... commands provide controls on implicit preload solution.
    - Set implicit step size **DT0** in *CONTROL_IMPLICIT_GENERAL
    - Leave **IMFLAG**=0 so only the precursor, preload solution is implicit
    - Other implicit controls are at the discretion of the analyst (static vs. implicit transient, automatic step adjustment, etc.)
  - Regular, explicit solution commences from t=0, starting from the preloaded state.

Preloading Bolts

- Iterative Loading Types
  - Require multiple runs to tune load in order to give desired bolt stress
  - *LOAD_THERMAL_LOAD_CURVE
  - *CONTACT_INTERFERENCE

- Non-iterative Loading Types
  - Bolt stress is specified directly.
  - *INITIAL_STRESS_SECTION
    - Solid elements only
  - *INITIAL_AXIAL_FORCE_BEAM
    - Type 9 beams only

*LOAD_THERMAL_LOAD_CURVE

- In this method, we shrink the bolt by cooling it. As the bolt contracts during the DR phase, preload is induced.
- Coefficient of thermal expansion (CTE) must be given for bolt material, e.g., via *MAT_ADD_THERMAL_EXPANSION.
- Negative temperature is prescribed using *LOAD_THERMAL_LOAD_CURVE.
  - **LCID** = curve of temperature vs. time for transient phase (constant T).
  - **LCIDDR** = curve of temperature vs. time for DR phase.
    - **SIDR**=1 in *DEFINE_CURVE.
    - Ramp T and then hold constant.
- Temperature T (or CTE) necessary to produce a target bolt stress σ can be estimated.
  - σ = E * CTE * -T
  - Adjust T (or CTE) in subsequent run to fine tune the final bolt stress
- Example: http://ftp.lstc.com/anonymous/outgoing/jday/bolt.thermal.k.gz

*CONTACT_..._INTERFERENCE

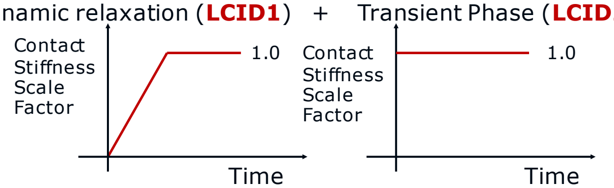
- Developed for modeling interference-fit assemblies.
- Define the mesh to include finite initial penetration between parts. The meshed geometry represents the unstressed state.
- Initial penetrations are not removed during start up of analysis but rather are allowed to generate contact forces.
- To avoid sudden, large contact forces, the contact stiffness is scaled with time using **LCID1** (DR phase) and **LCID2** (Transient phase).
- Shell thickness offsets are considered.
- Orientation of contact segments is important.

- Keyword commands for interference contact:
  - *CONTACT_NODES_TO_SURFACE_INTERFERENCE
  - *CONTACT_ONE_WAY_SURFACE_TO_SURFACE_INTERFERENCE
  - *CONTACT_SURFACE_TO_SURFACE_INTERFERENCE

*CONTACT_…_INTERFERENCE

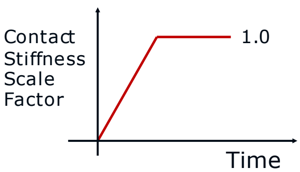
If DR phase is included,

Dynamic relaxation (**LCID1**) + Transient Phase (**LCID2**)



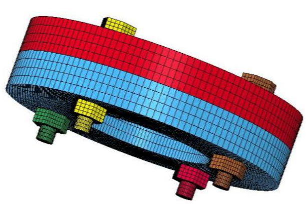
Or if no DR phase,

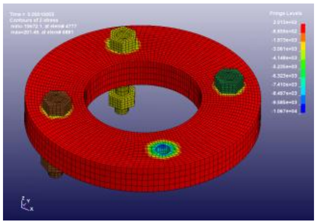
Transient Phase Only (**LCID2**) if LCID1=0



*CONTACT_…_INTERFERENCE

Example:
http://ftp.lstc.com/anonymous/outgoing/jday/bolt.interf.k.gz





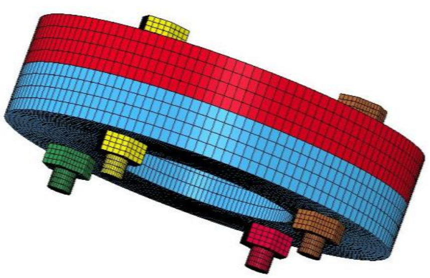
- Four bolts clamp 1.0" thick, solid rings together.
- Mesh is defined so each bolt head and each nut overlap (penetrate) the solid ring surface by 0.003".
  - Trial overlap based loosely on target bolt stress/(bolt length * E)
- *CONTACT_SURFACE_TO_SURFACE_INTERFERENCE defined between overlapping surfaces.
- Contact stiffness is ramped up during DR phase.
- Overlap can be adjusted in subsequent trials to fine tune the bolt stress.

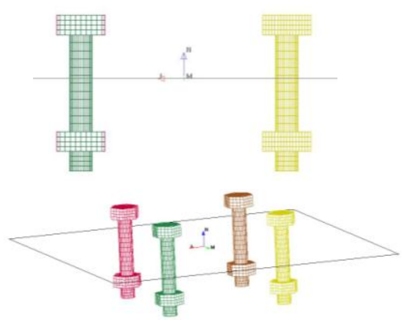
Preloading Bolts Modeled with Solid Elements

- *INITIAL_STRESS_SECTION is yet another method for preloading bolts. It acts by prescribing a stress value to solid elements cut by a cross-section.
  - Stress (normal to the cross-section) is defined via *DEFINE_CURVE (stress vs. time).
    - This curve is typically flagged with **SIDR**=1, so that dynamic relaxation is invoked for applying the preload.
    - Curve should ramp stress from zero and then hold target stress value long enough for a state of near equilibrium in the model to be reached, i.e., long enough for DR to converge.
  - Physical location of cross-section is defined via *DATABASE_CROSS_SECTION.
  - A part set, together with the cross-section, identify the elements subject to the prescribed stress.
  - Contact damping (VDC) and/or *DAMPING_PART_STIFFNESS may be necessary to attain convergence during the DR phase.

*INITIAL_STRESS_SECTION

Example:
http://ftp.lstc.com/anonymous/outgoing/jday/bolt.initial_stress_section.4not1.k.gz

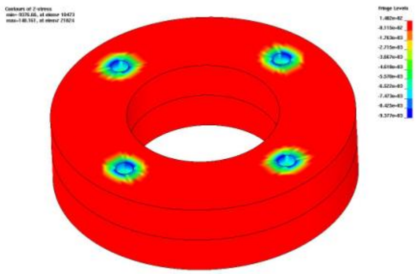


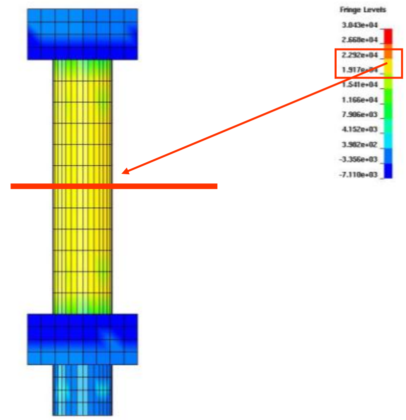


- Four bolts clamp 1.0" thick, solid rings together.
- A cross-section is defined that cuts through the bolts somewhere in the middle.
- The bolt elements cut by the cross-section have longitudinal stress ramped to 20,000 psi during DR phase using *INITIAL_STRESS_SECTION.
- The direction of prestress is normal to the plane.

*INITIAL_STRESS_SECTION

Example of preloaded solid bolts





Target bolt stress is achieved directly without the need for multiple trial simulations.

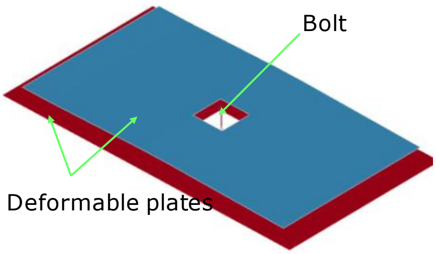
Preloading Bolts Modeled with Beam Elements

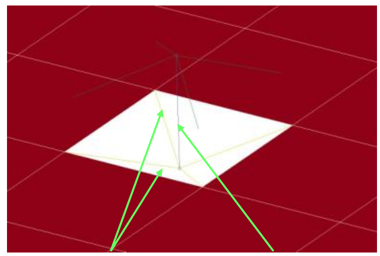
- *INITIAL_AXIAL_FORCE_BEAM will preload beam elements to a prescribed axial force.
  - The preload curve (axial force vs. time) is defined with *DEFINE_CURVE.
    - The curve is typically flagged with **SIDR**=1 so preload is applied during the DR phase.
    - Curve should ramp force from zero and then hold target force value long enough for a state of near equilibrium in the model to be reached, i.e., long enough for DR to converge.
  - The beams to be loaded are given by *SET_BEAM.
  - Beam formulation (**ELFORM**) must be set to 9 (spot weld beam) and the material model should be *MAT_SPOTWELD.
  - Contact damping (**VDC**=20) is recommended.
  - *DAMPING_PART_STIFFNESS (**COEF**=0.1) may speed up convergence during DR phase.

*INITIAL_AXIAL_FORCE_BEAM

Example:
http://ftp.lstc.com/anonymous/outgoing/jday/initial_axial_force_beam_drelax.k

- The bolt is modeled with a type 9 beam and *MAT_100.
- The bolt beam is attached to the plates being bolted by 4 rigid beams at each end.
- The bolt is preloaded by ramping the axial force to 0.05 during the DR phase using *INITIAL_AXIAL_FORCE_BEAM.
- No additional load is applied in subsequent transient phase.

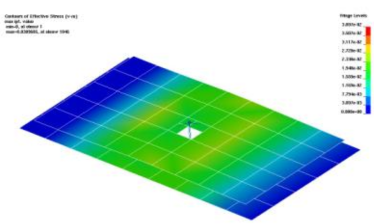




*INITIAL_AXIAL_FORCE_BEAM

Example of preloaded beam bolt (cont'd)

Stress at conclusion of DR phase due to bolt preload.



Axial force in bolt is successfully initialized