Preloads in LS-DYNA

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    - Implicit
  - Transient Explicit with Mass Damping
  - Implicit Analysis
- Bolt Preload Techniques
  - Thermal
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  - Stress in Solid Cross-section
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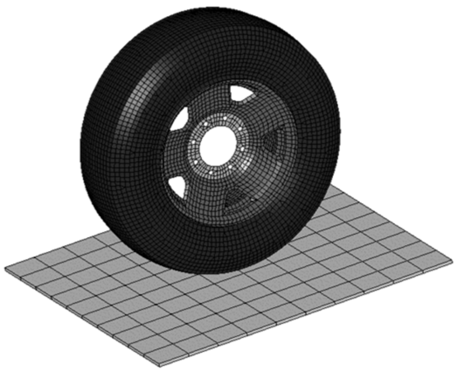
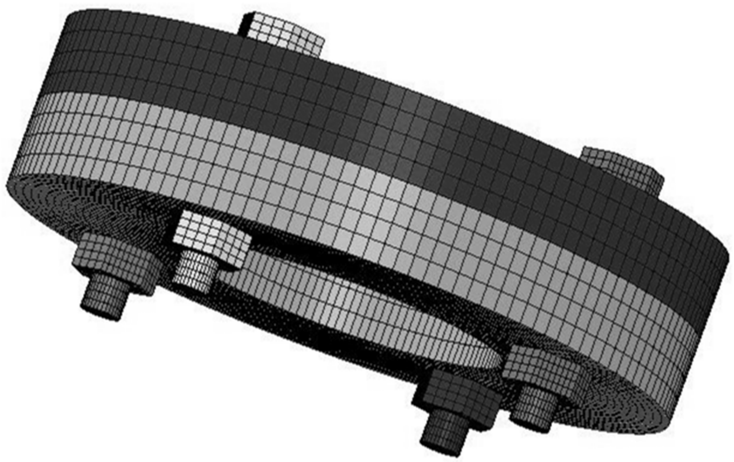
Preload - Introduction

- Sometimes it is 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
  - Shrink-fit parts
  - Stresses induced by a torqued bolt



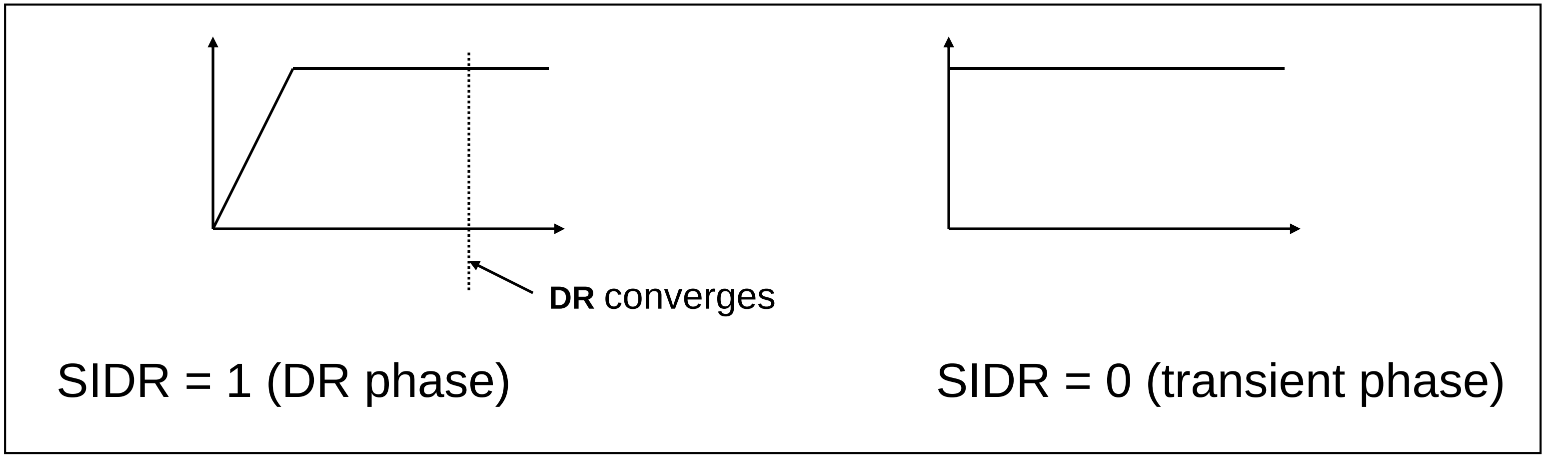


Explicit Dynamic Relaxation (DR)

- Explicit DR is an *optional* transient analysis that takes place in ‘pseudo-time’ (precedes regular 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 timestep by the dynamic relaxation factor (default = .995). Thus the solution undergoes a form of damping during DR.
- The distortional kinetic energy is monitored. When this KE has been sufficiently reduced, i.e., the “convergence factor” has become sufficiently small, the DR phase terminates and the solution automatically proceeds to the transient analysis phase.
- Alternately, DR can be terminated at a preset termination time.

Explicit Dynamic Relaxation

- DR is typically invoked by setting parameter SIDR in a load curve (*DEFINE_CURVE) to 1 or 2.
- Ramp the load during DR phase and then hold load constant until solution converges
  - Make sure convergence occurs *after* 100% of preload is applied
- Maintain the preload in subsequent transient analysis phase (use separate load curve without the ramp)



Explicit Dynamic Relaxation

*CONTROL_DYNAMIC_RELAXATION

*CONTROL_DYNAMIC_RELAXATION parameters

- Iterations between convergence check (default=250)
  - Also affects output interval for "d3drlf"
- Convergence tolerance (default 0.001)
  - Ratio of distorsional KE at convergence to peak distorsional KE
  - Smaller value results in converged solution nearer to steady state but run will take longer to get there
- Dynamic relaxation factor (default=0.995)
  - Reduction factor for nodal velocities each time step
  - If value is too small, model never reach steady state due to overdamping
- Optional termination time for DR (default = infinity)
  - DR will stop if time reaches DRTERM even if convergence criterion not satisfied
- Time step scale factor used during DR

Dynamic Relaxation

*CONTROL_DYNAMIC_RELAXATION

*CONTROL_DYNAMIC_RELAXATION parameters

- IDRFLG
  - Flag to activate DR (not required if DR is activated with *DEFINE_CURVE)
  - Set to 2, will invoke a completely different and faster initialization approach ... Initialization by Prescribed Geometry.
    - Requires supplemental input file containing nodal displacements and rotations ("m=filename" on execution line).
      - Such a file *drdisp.sif* is written at conclusion of standard DR run.
      - If nodal rotations are not included in file, method is invalid for beams and shells.
    - LS-DYNA® runs a short transient analysis of 100 timesteps to preload the model by imposing the nodal displacements and rotations.
    - Solution then proceeds with regular transient analysis.
  - Set to 5, activates **implicit** method for solution of preloaded state
    - Must also set DRTERM to signal end of DR phase.
    - *CONTROL_IMPLICIT... provide controls on implicit phase.

Dynamic Relaxation

Output Related to Dynamic Relaxation

- ASCII output files are NOT written during DR phase, e.g., *glstat*, *matsum*, *rcforc*, etc. The binary *d3thdt* file can be used if IDRFLG=-1.

- Binary database, *d3drlf*, is written by including command *DATABASE_BINARY_D3DRLF. Set output interval to 1. This will cause a state to be written each time convergence is checked during DR
  - Plotting time histories from *d3drlf* with LS-PrePost® allows user to confirm solution is near steady state

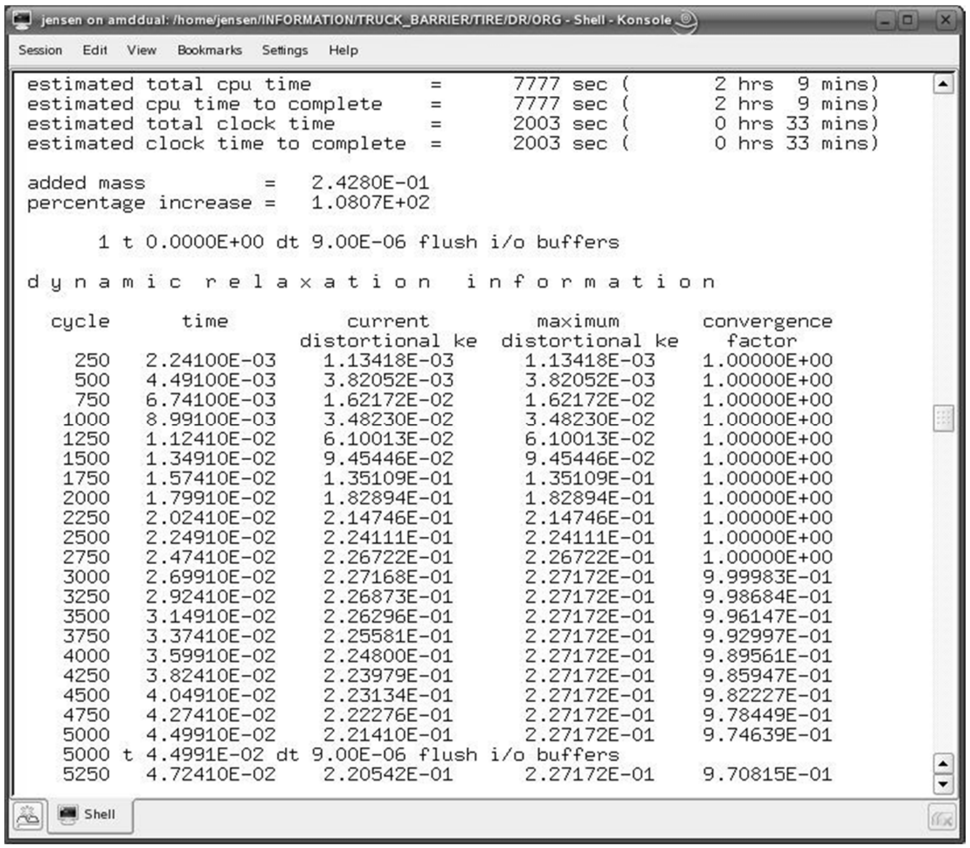
- *relax* file is automatically written and contains record of convergence history. Data can be plotted with LS-PrePost.

- *drdisp.sif* contains nodal displacements and rotations at conclusion of DR phase.

Explicit Dynamic Relaxation

Output Related to Explicit Dynamic Relaxation

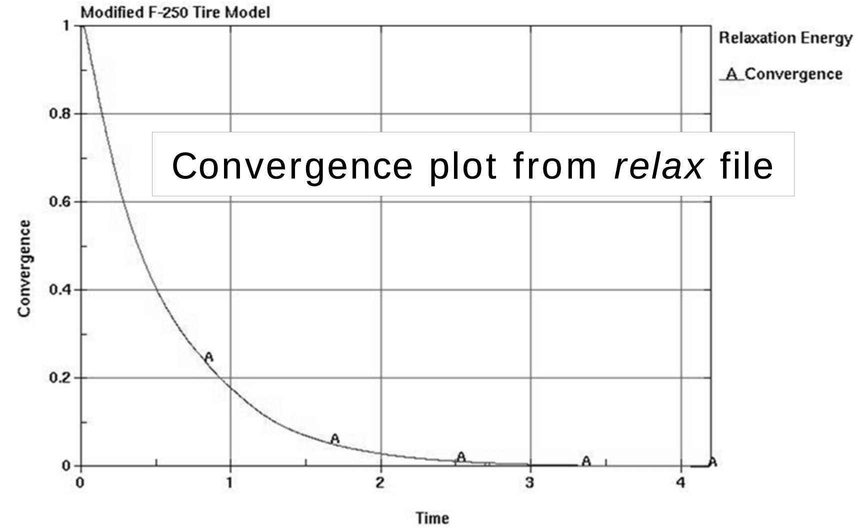
Dynamic Relaxation information is written to the screen. The transient phase starts when the convergence tolerance or a Specified termination time is reached.


jensen on amddual: /home/jensen/INFORMATION/TRUCK_BARRIER/TIRE/DR/ORG - Shell - Konsole

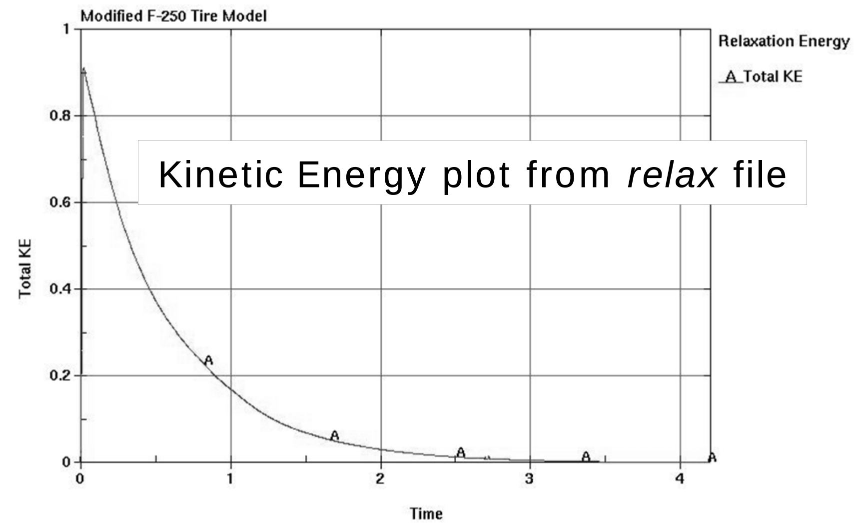
Session Edit View Bookmarks Settings Help

```
 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
```

Shell



Convergence plot from *relax* file



Kinetic Energy plot from *relax* file

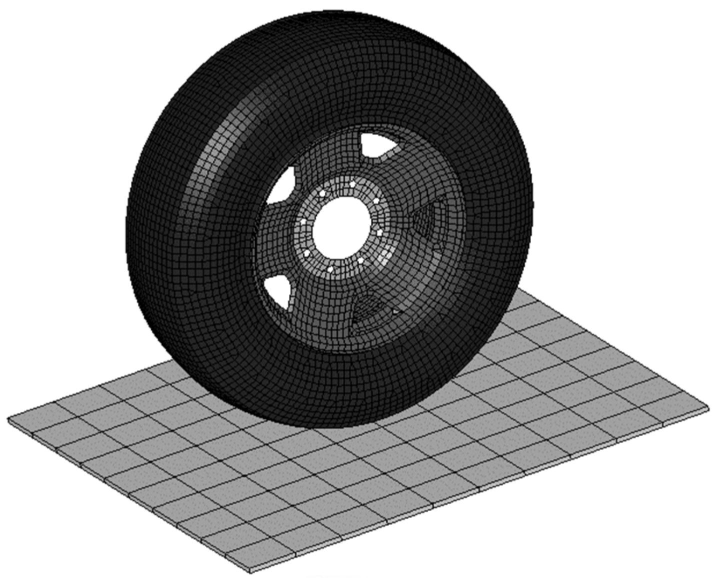
Dynamic Relaxation

Typical Loads During Dynamic Relaxation

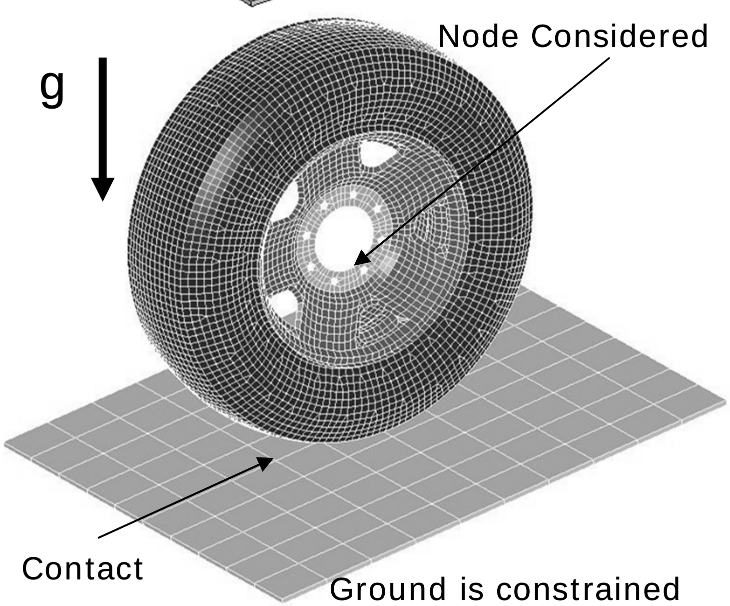
- Gravity loads and centrifugal loads (spinning bodies) are imposed using *LOAD_BODY_option.
  - LCID and LCIDDR are separate curves for transient phase and DR phase, respectively.
- Thermal stresses can be imposed using *LOAD_THERMAL_LOAD_CURVE.
  - Parts, e.g., bolts, defined with a coefficient of thermal expansion will have thermal stresses imposed.
  - LCID and LCIDDR are separate curves for transient phase and DR phase, respectively.
- Other load types or boundary conditions are applied during DR if SIDR in corresponding *DEFINE_CURVE is set to 1 or 2. Example: *LOAD_SEGMENT, *BOUNDARY_PRESCRIBED_MOTION.
- *CONTACT_…_INTERFERENCE imposes load associated with geometric interference.
- *INITIAL_... (more on that later)

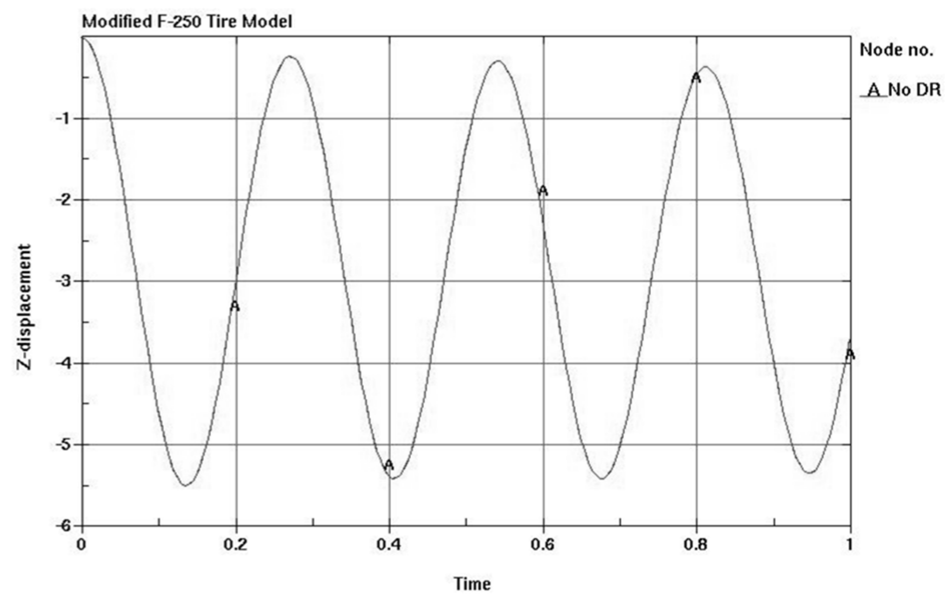
Explicit Dynamic Relaxation

Example – Gravity Loading on a Tire



- One of the tires from NCAC's Ford 250 was used in this example but without the control volume. A gravity load is applied in the transient phase as a constant curve, which makes the tire bounce during the simulation (time =1) as seen when plotting the Z-displacement for a node on the tire rim. This model is used to investigate the behavior of Dynamic Relaxation.

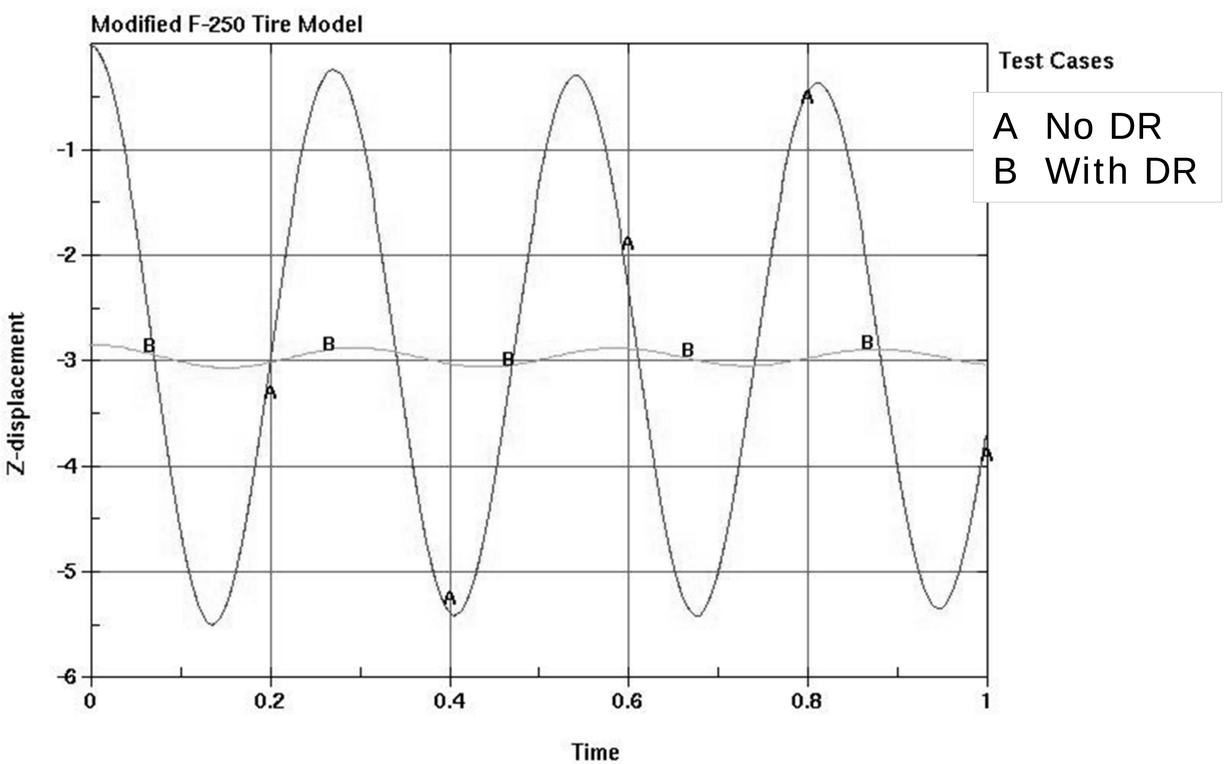




Dynamic Relaxation

Example – Gravity Loading on a Tire

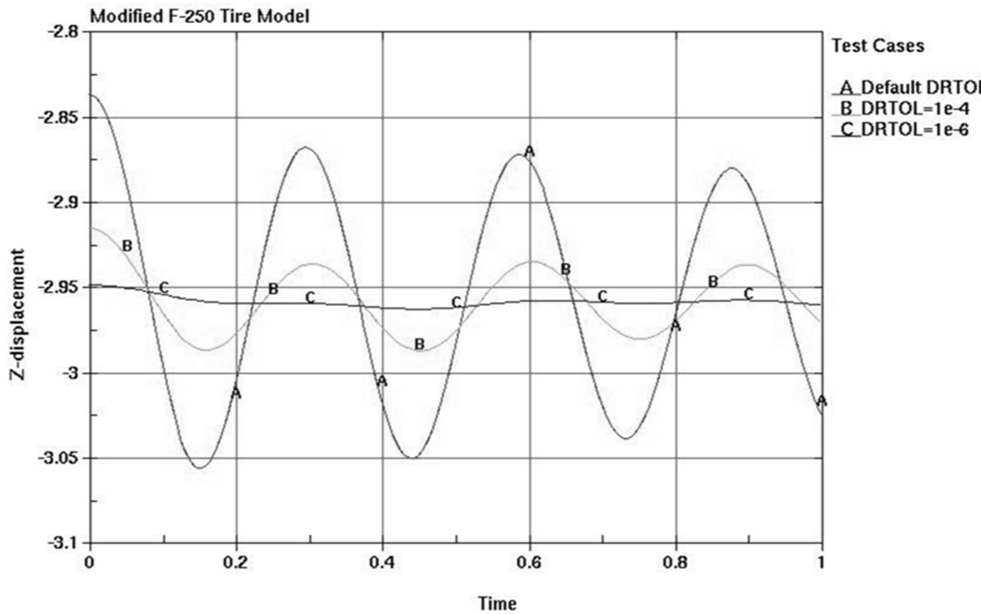
- Dynamic Relaxation was added to the model using a ramped load curve for the DR phase, i.e., load curve LCIDDR (*LOAD_BODY_Z) has SIDR (*DEFINE_CURVE) set to 1. The load is ramped in curve LCIDDR over 2000 time steps. The *CONTROL_DYNAMIC_RELAXATION parameters are all set to default and the deck is the same as before.



Dynamic Relaxation

Example – Gravity Loading on a Tire

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



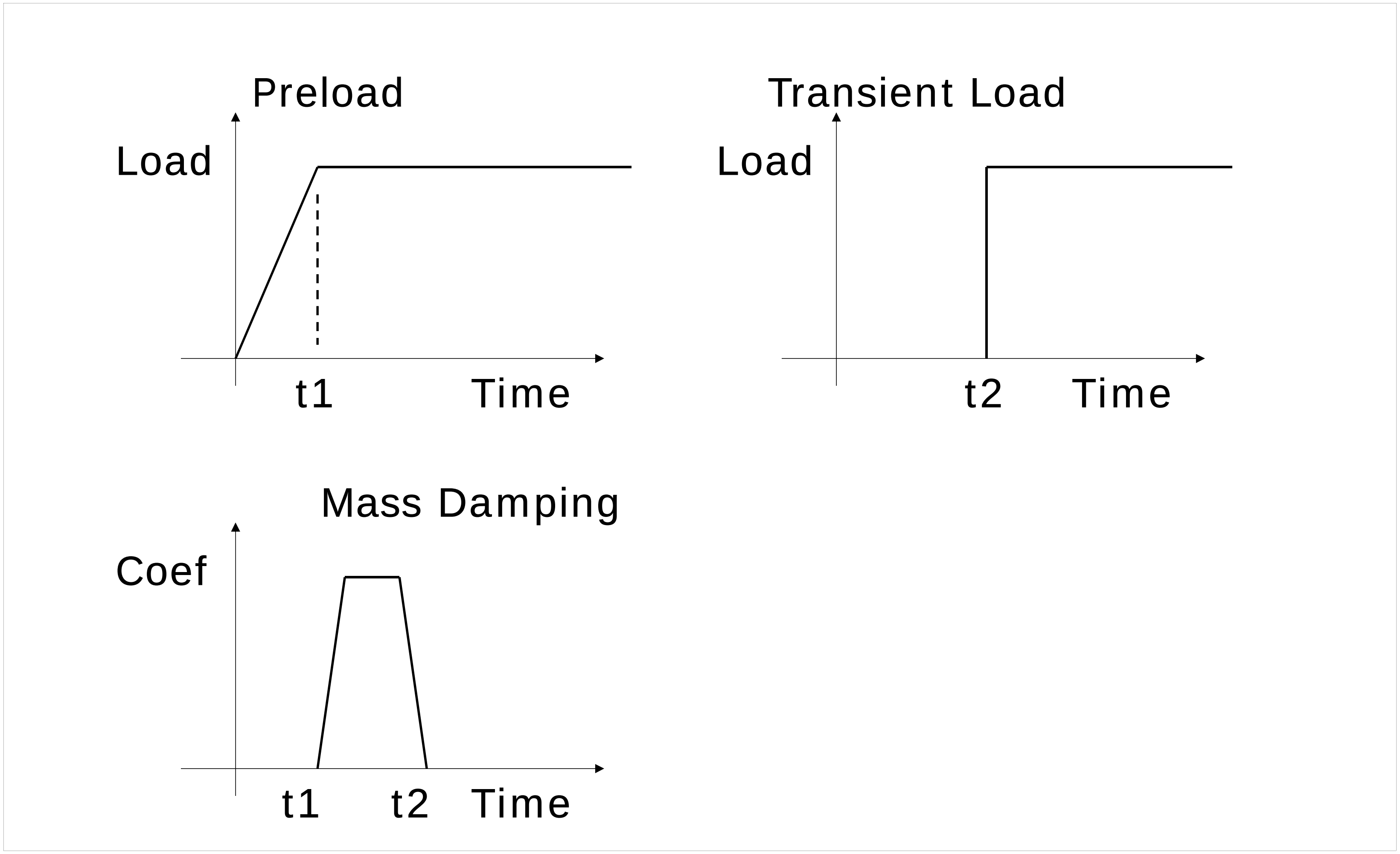
- The value of DRTOL offers a tradeoff between run time and amplitude of residual dynamic oscillation.

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

Transient Stress Initialization

- As an alternative to using DR, in some cases the preload can be established in the early part of the regular transient simulation.
  - Use *initial_velocity_generation_start_time for problems whose transient response is driven by initial velocity.
    - Delays onset of “initial” velocity.
  - Ramp up preload quasi-statically and then hold steady.
  - Use time-dependent mass damping (*DAMPING_GLOBAL) to impose near-critical damping until preload is established.
    - Drop damping constant to zero after preload is established and transient loading is ready to be applied.
  - Apply transient loads AFTER preload is established.
    - Use nonzero birthtime or arrival time for transient loads

Transient Stress Initialization



Preload via Implicit Analysis

- Recall that true static analysis is possible by invoking implicit analysis in LS-DYNA®. Static analysis is well-suited to inducing preload. However, no rigid body modes can be present for a static analysis. One has the option of **dynamic** implicit combined with an extended loading period.

- Implicit analysis is invoked via the command *CONTROL_IMPLICIT_GENERAL.

- Other implict-related commands often used are:
  - *CONTROL_IMPLICIT_AUTO automatically adjusts step size based on ease or difficulty in achieving convergence.
  - *CONTROL_IMPLICIT_DYNAMICS can make the implicit solution dynamic rather than static.
    - Invoking dynamics can ease convergence.
    - Step size has units of time if dynamics is invoked.

Preload via Implicit Analysis

- Approach 1: Two separate analyses.
  - Make an implicit (or explict) simulation of the preload. In the input deck specify *INTERFACE_SPRINGBACK_LSDYNA. This creates an ASCII file called *dynain* when the simulation is finished. The *dynain* file contains keyword commands describing the deformed geometry, stresses, and plastic strains. Merge these commands into the original deck, deselect the implicit cards, modify the loads, and run a second, explicit simulation.
    - 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 only data from the *d3plot* database, LS-PrePost® can output a *dynain* file via Output > Format: Dynain Ascii > Write.

Preload via Implicit Analysis

- Approach 2: Single, switched analysis.
  - Use one input deck where switching between implicit and explicit 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 at *CONTROL_IMPLICIT_GENERAL to -|curve ID|. Switching from one analysis to the other is seamless and has no CPU or I/O overhead.

- Approach 3: Implict DR (mentioned previously).

Bolt Preload

- 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

- Idea is to shrink the bolt by cooling it. As bolt contracts during 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) to produce a target bolt stress σ can be estimated.
  - σ = E * CTE * -T
  - Adjust T (or CTE) in subsequent run to fine tune bolt stress
- Example: http://ftp.lstc.com/anonymous/outgoing/jday/bolt.thermal.k.gz

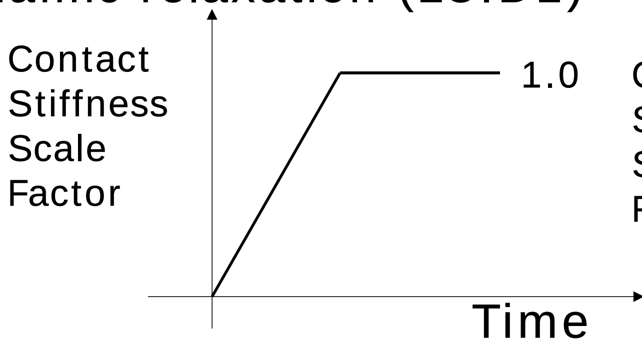
*CONTACT_..._INTERFERENCE

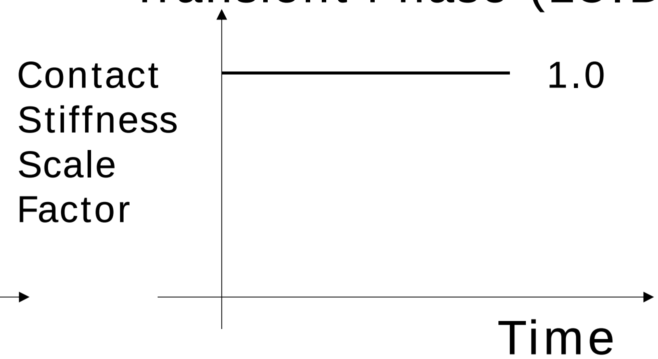
- Developed for modeling shrink-fit parts.
- Define the initial geometry to include finite initial penetration between parts. Parts are initially in an unstressed state.
- The initial penetration check is not done for ths contact type.
- To avoid sudden, large contact forces, the contact stiffness is scaled with time using LCID1 (DR phase) and LCID2 (Transient phase).
- Shell thickness offsets are considered.
- Segment orientation is important. Orient the normals correctly – facing against opposing contact surface.
- Specify the contact using segment sets.

- Types:
  - *CONTACT_NODES_TO_SURFACE_INTERFERENCE
  - *CONTACT_ONE_WAY_SURFACE_TO_SURFACE_INTERFERENCE
  - *CONTACT_SURFACE_TO_SURFACE_INTERFERENCE

*CONTACT_..._INTERFERENCE

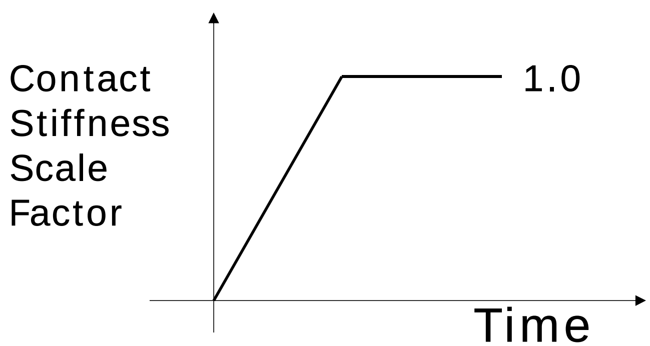
Dynamic relaxation (LCID1) + Transient Phase (LCID2)





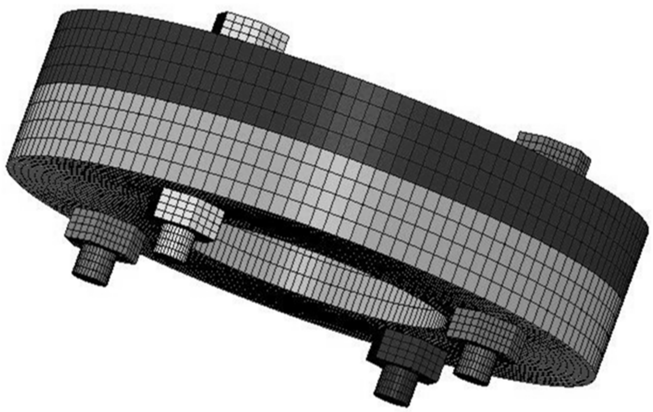
OR

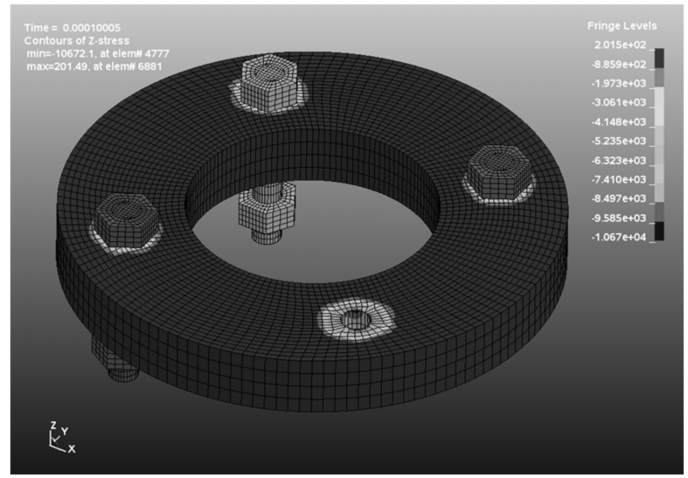
Transient Phase Only (LCID2) if LCID1=0



*CONTACT_…_INTERFERENCE

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





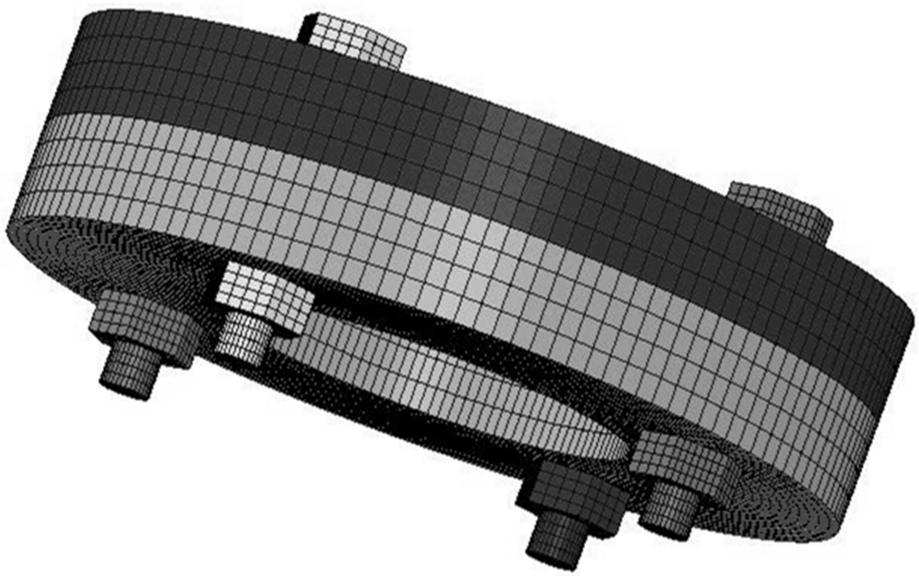
- Four bolts clamp two, 1.0” thick solid rings together.
- Mesh is defined so each bolt head and each nut overlap (penetrate) the solid ring surface by 0.003”.
  - Trial overlap based loosely on target bolt stress/(bolt length * E)
- *CONTACT_SURFACE_TO_SURFACE_INTERFERENCE defined between overlapping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

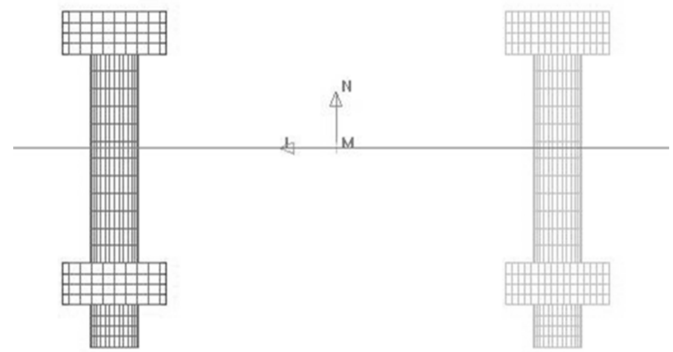
Preloading a Solid Cross-section to a Known Stress

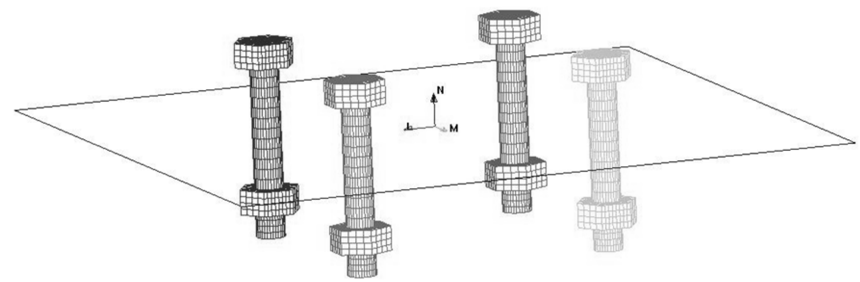
- *INITIAL_STRESS_SECTION will preload a cross-section of <u>solid</u> elements to a prescribed stress value
  - Preload stress (normal to the cross-section) is defined via *DEFINE_CURVE (stress vs. time)
    - This curve is typically flagged with SIDR=1, so that dynamic relaxation is invoked for applying the preload
    - Stress should be ramped from zero
  - 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 preload stress
  - Contact damping (VDC) and/or *DAMPING_PART_STIFFNESS may be required to attain convergence during the dynamic relaxation analysis

*INITIAL_STRESS_SECTION

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



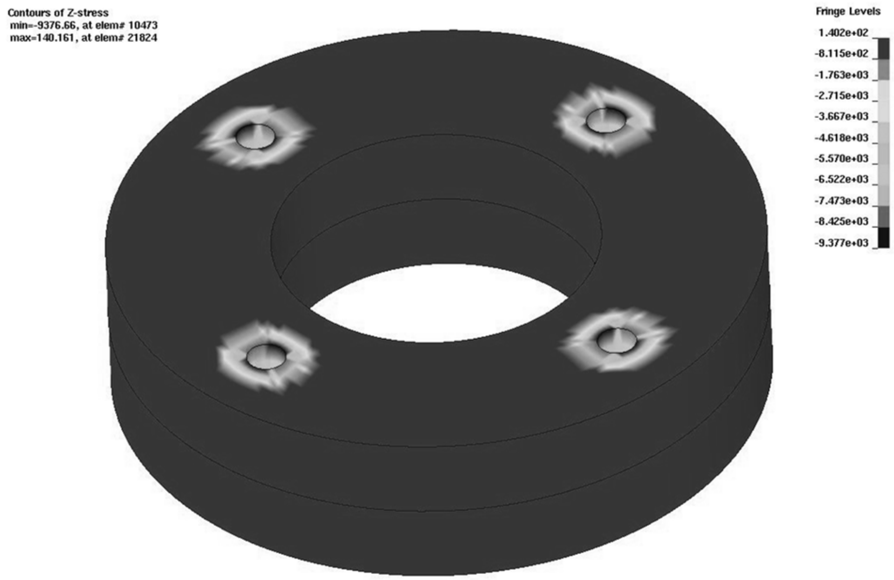


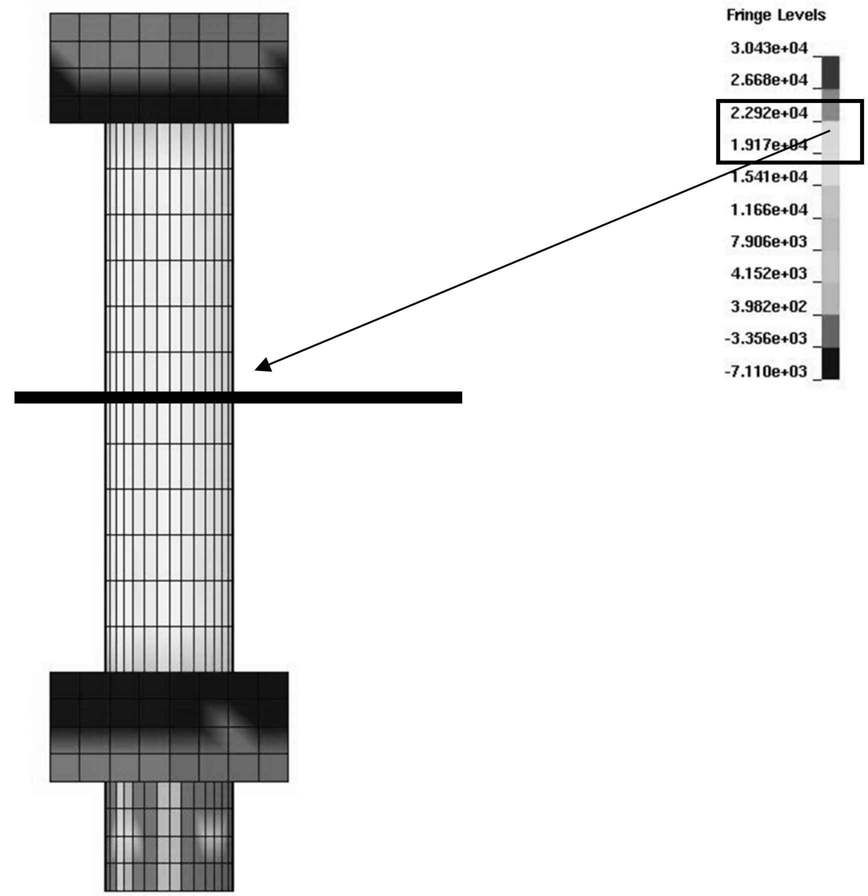


- Four bolts clamp two, 1.0” thick solid rings together.
- The four bolts are given a prestress of 20,000 psi using *INITIAL_STRESS_SECTION.
- The sections being preloaded are defined by a plane through the middle of the bolts.
- The direction of prestress is normal to the plane.

*INITIAL_STRESS_SECTION

Example of preloaded bolts





Target bolt stress is achieved without multiple trial simulations.

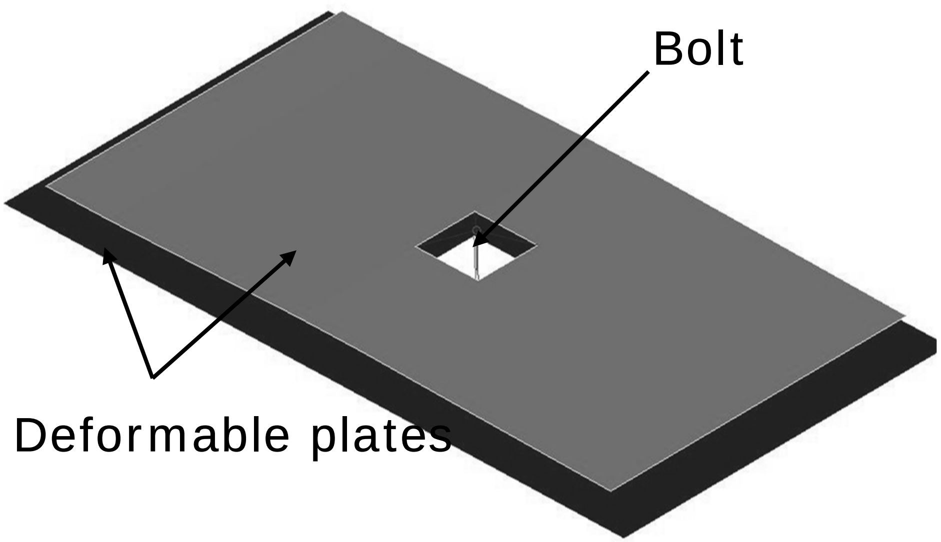
Initial Forces in a Beam

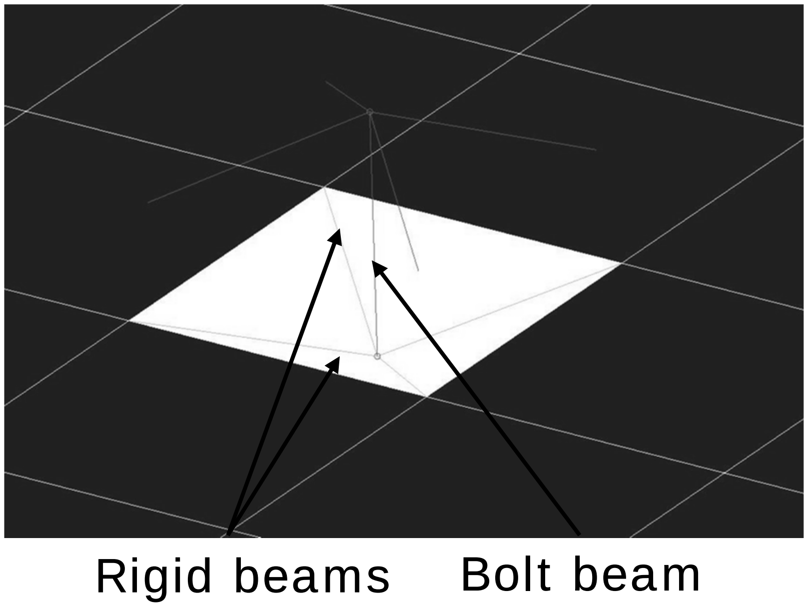
- *INITIAL_AXIAL_FORCE_BEAM will preload beam elements to a prescribed axial force.
  - The preload curve (axial force vs. time) is defined with *DEFINE_CURVE.
    - The curve is typically flagged with SIDR=1 so preload is applied during a DR phase.
    - Curve should ramp up beam force to ease convergence.
  - The beam to be loaded is given by a SET_BEAM.
    - Beam formulation (ELFORM) must be set to 9 (spot weld beam).
    - Use with *MAT_SPOTWELD.
    - The spot weld beams initialized in this manner will not be excluded from automatic contacts.
  - For models with contact, damping in the contact (VDC=20) is recommended.
  - *DAMPING_PART_STIFFNESS may promote convergence during DR phase.

Initial Forces in a 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 deformable bolt beam is attached to the plates being bolted by rigid beams.
- The bolt is preloaded with a force of 0.05 using *INITIAL_AXIAL_FORCE_BEAM.
- The load curve is applied in DR phase with a ramp function.
- No additional load is applied in subsequent transient phase.

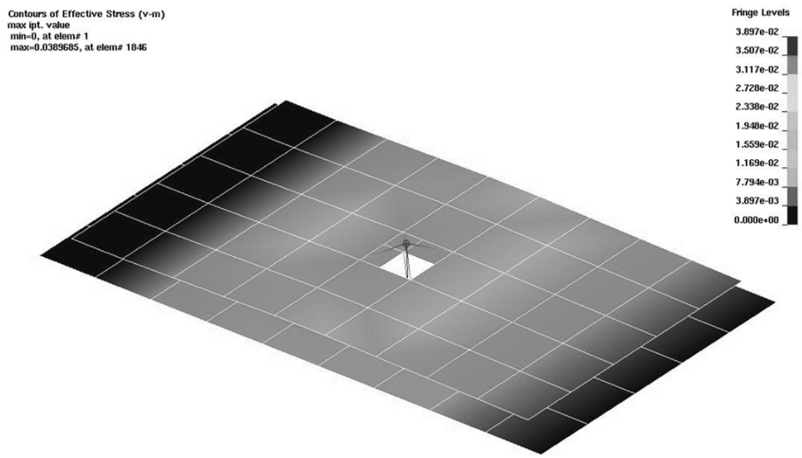




Initial Forces in a Beam

Example of preloaded bolt

- Stress at conclusion of DR phase due to bolt preload.



- Axial force in bolt is successfully initialized