Bolts in Nonlinear and Dynamic Analyses

Best Practices and Results Validation

Ansys

Effect of Bolt Preload on Dynamic Characteristics

- Insufficient bolt preload may cause large vibrations or wobbling in case of a rotating machine. This may lead to eventual failure of an assembly.
- When bolts are tightened, the bolts are under tensile load, and mating parts are under compressive loads.
- This initial stress state, caused due to bolt preload, changes the stiffness of the assembly.
- For example, when the applied bolt preload is insufficient, mating parts can move relative to each other, resulting in reduced stiffness of the assembly.
- This change in stiffness leads to a change in the natural frequency of the assembly.

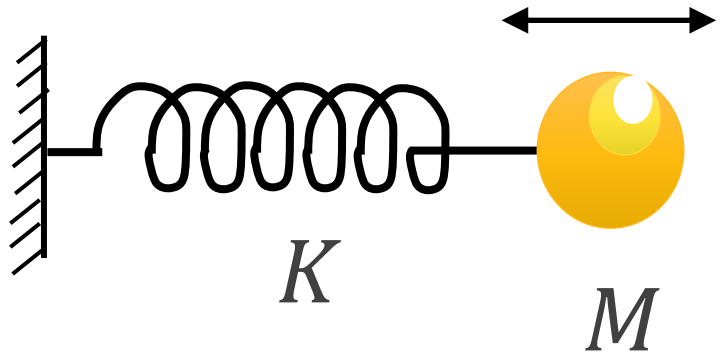


Insufficient bolt preload may cause wobbling and lead to eventual failure

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Why Does Prestress Affect the Natural Frequencies of a System?

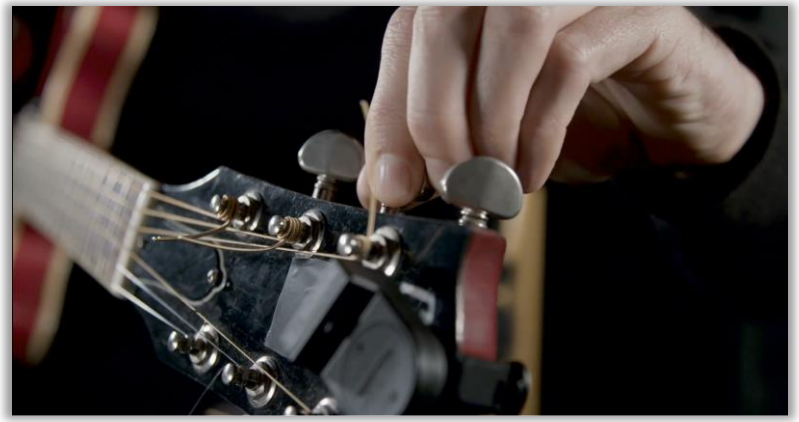
- In a spring-mass system, if the mass is displaced by some amount and then let go, the system starts to oscillate with a constant frequency, known as the natural frequency of the spring-mass system.
- Natural frequency $\psi = \sqrt{\frac{K}{M}}$,where K is the spring stiffness and M is the mass attached. Thus, the natural frequency of a system depends on its stiffness and mass.



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Why Does Prestress Affect the Natural Frequencies of a System? (cont.)

- For example, in a guitar, different strings have different thicknesses (and hence different masses) which results in different natural frequencies for each string.
- However, the natural frequency of a guitar string can also be changed by altering the stiffness of the string.
- This is done by tuning a guitar, which effectively stretches or loosens a string.
- Thus, applying an initial stress (during the tuning process) changes the stiffness of the string, which in turn changes its natural frequency.
- Usually, prestressing in tension causes natural frequencies to increase while prestressing in compression causes natural frequencies to decrease.
- Since bolt preload changes the initial stress state of an assembly, it may affect the natural frequencies of the assembly.



Tuning the guitar changes its natural frequency

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Governing Equation of Dynamic Systems

- To solve for the response of a general dynamic system, we solve the following equations:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f(t)\}$$

Mass — Acceleration; Damping — Velocity; Stiffness — Displacement; Load

- For an undamped system, the damping terms can be eliminated.

$$[M]\{\ddot{u}\} + [K]\{u\} = \{f(t)\}$$

- In systems where inertial effects are negligible (static system), we may eliminate the mass term too.

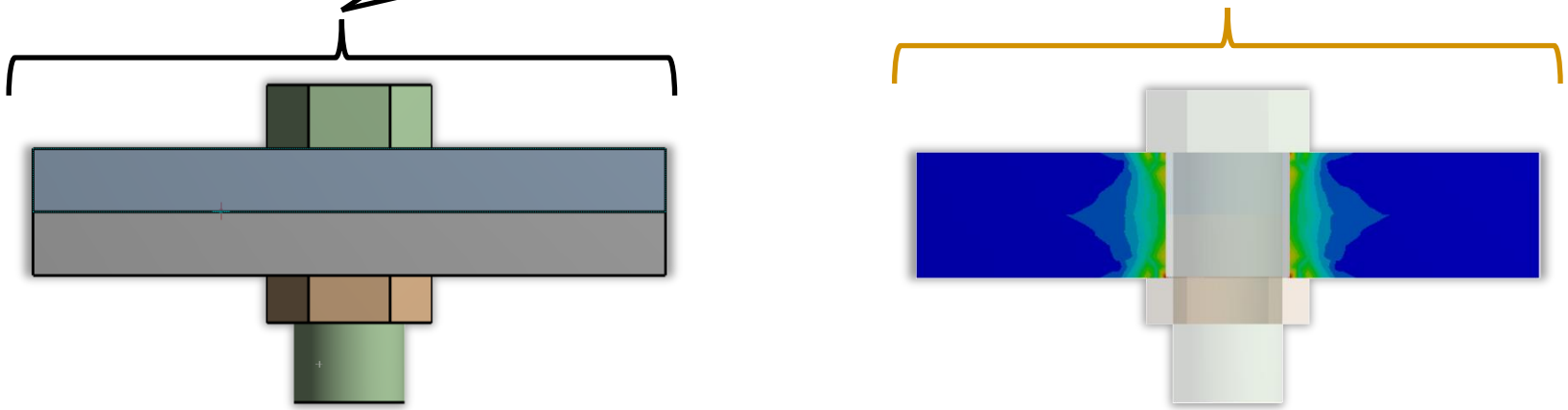
$$[K]\{u\} = \{f(t)\}$$

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Governing Equation of Dynamic Systems (cont.)

- The presence of stresses in a system changes its stiffness.
- This change in stiffness is captured by a stress stiffening matrix, [S].
- In the case of pre-stressed systems such as preloaded bolted joints, this term is added to the stiffness matrix.

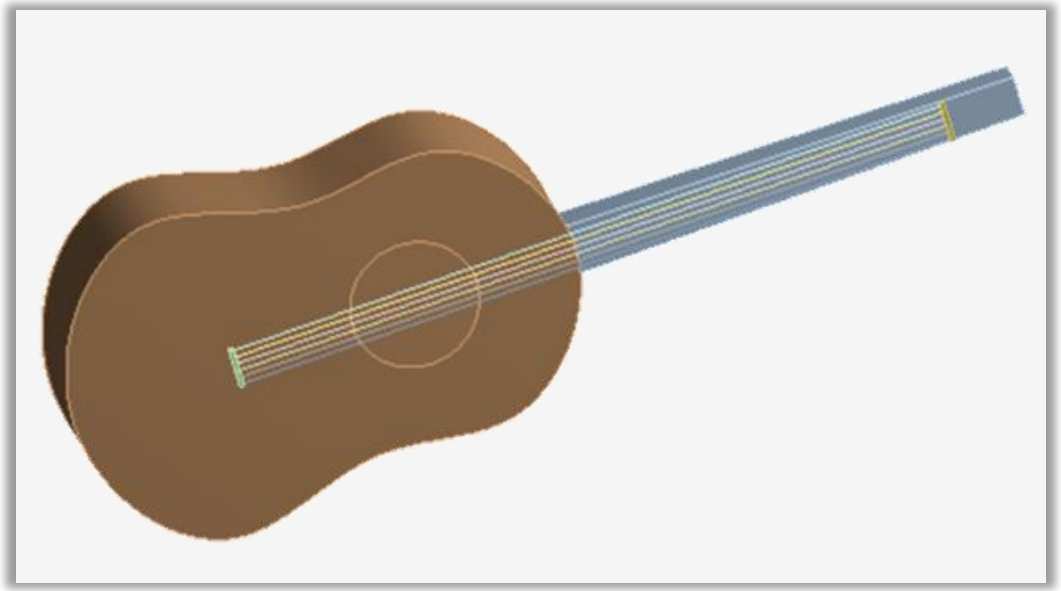
$$[M]\{\ddot{u}\} + [K + S]\{u\} = 0$$



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Example for Pre-stressed Modal Analysis

- Let's calculate the natural frequency of guitar strings to see how pre-stress affects the system.
  - A displacement control is applied on the strings to put the strings in tension.
  - The natural frequencies of the strings are drastically increased because of the pre-stressed effect.



Calculating the natural frequencies of a guitar before and after pre-stress is applied

Before Pre-stress

Mode	Frequency (Hz)
1	1.7677
2	1.7677
3	3.0051
4	3.01
5	4.87
6	4.87
7	5.1264
8	5.1264
9	8.2838
10	8.2838

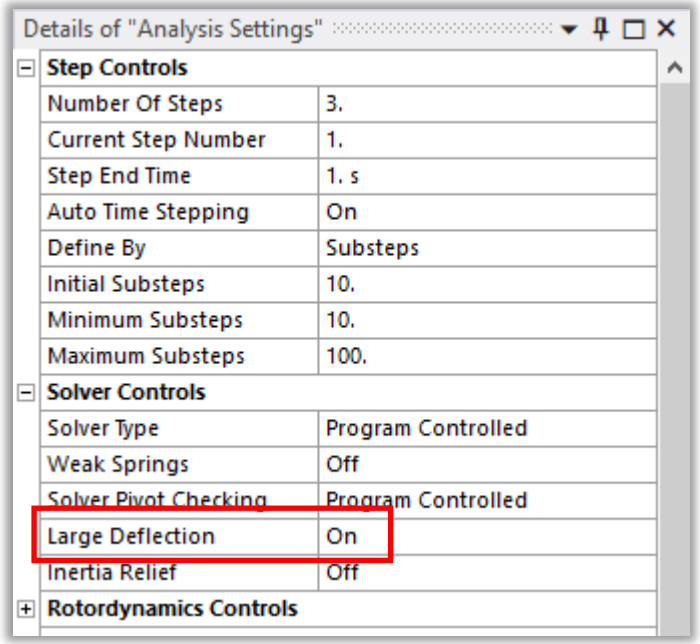
After Pre-stress

Mode	Frequency (Hz)
1	187.54
2	187.54
3	187.89
4	187.89
5	188.5
6	188.5
7	190.56
8	190.56
9	193.95
10	193.95

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Large Deformation

- This formulation is used when the shape of the system changes significantly and/or there's stress developed in the part.
- Large deformation accounts for the following nonlinearities:
  - Large strain
  - Large rotation
  - Stress stiffening (introduces stiffening matrix, [S])
  - Spin softening (introduces softening matrix, [S'])
- In the case of preloaded bolted joints, large strain and stress stiffening play major roles in influencing the dynamic characteristics of the structure.



Using large deformation considers both change in shape and stress stiffening.

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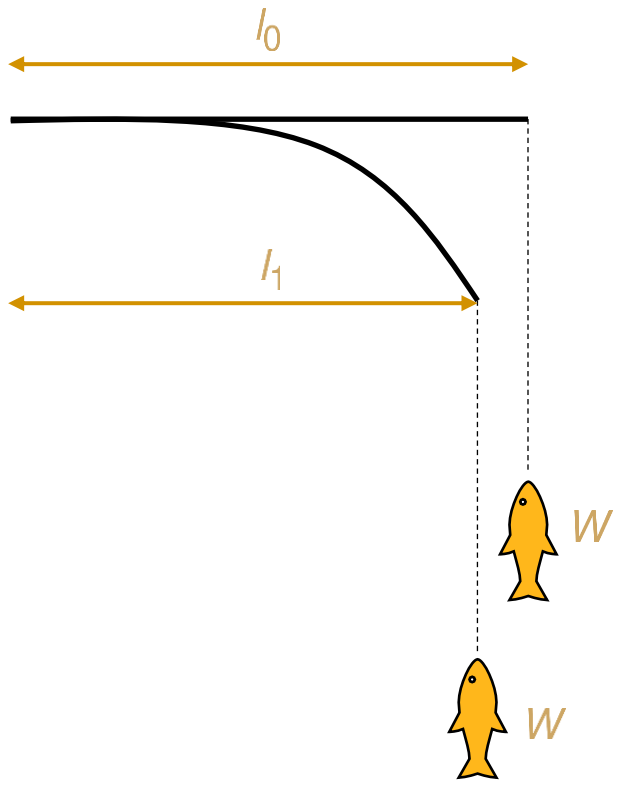
Large Deformation (cond.)

- In a fishing rod the weight of the fish results in bending of the fishing rod significantly.
- Large strain nonlinearity is in play here, so we need to use large deformation analysis.
- Let's solve this using both the small and large strain formulations to see how they impact the solution.

$$M_0 = W \times l_0$$

$$M_1 = W \times l_1$$

- As "l" decreases, M decreases and the tip deflection must decrease.
- Also, the fishing rod gets stiffer due to stress.



Use large deformation to consider shape changes.

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When to Turn On Large Deformation?

- Turning ON large deformation invokes a nonlinear solver which is computationally expensive.
- In a multistep analysis, large deformation is used in all the steps.
- Instances when large deformation must be turned ON:
  - When mating parts or bolts have material nonlinearities
  - When there are nonlinear contacts such as frictional contact
  - When parts undergo large deformations (e.g., gaskets, seals, etc.)
  - When sliding of components is of interest in the analysis (e.g., shear joints)



When unclear, run two cases, one with and one without large deformation. to decide before running design iterations.

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When to Turn On Large Deformation? (cont.)

- The overall stiffness of a system, [K], may or may not change due to deformation.
- If there are material or contact nonlinearities in the system, then the equations for such a system change to;

$$[M]\{\ddot{u}\} + [\overbrace{K + Kmat + Kcontact}^{[K']} + S' + S]\{u\} = 0$$

K_{mat} → change in stiffness due to material nonlinearity
$K_{contact}$ → change in stiffness due to contact nonlinearity
S' → change in stiffness due to spin softening
S → change in stiffness due to stress stiffening

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Natural Frequencies of Bolted Structures

- In bolted structures, the mass and stiffness are distributed across different parts.
- Due to bolt preload, their natural frequencies are influenced by the pre-stress in the system.
- We first solve for a modified stiffness matrix (due to stress stiffening and any material/contact nonlinearities). This is called **stress analysis** (static or transient).
- We then solve for natural frequencies by solving the equations for a pre-stressed, undamped system under no exciting loads. This is called **modal analysis**.

$$[K]\{u\} = \{f(t)\}$$



[K'], [S]

$$[M]\{\ddot{u}\} + [K' + S]\{u\} = \{0\}$$



Modal analysis

$$\{\Psi^i\}, \{\Phi^i\}$$

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Modal Analysis Based on Linear Perturbation

- Linear perturbation (LP) is used for performing modal analysis.
- LP uses a base analysis (static or transient analysis) to calculate the solution matrices (mass and stiffness) of a system and calculates natural frequencies in that state.
- If base analysis is linear, or if the base analysis is solved using small deformation, then LP uses the sum of the original stiffness matrix and the stress stiffening matrix.

$$[M]\{\ddot{u}\} + [K + S]\{u\} = 0$$

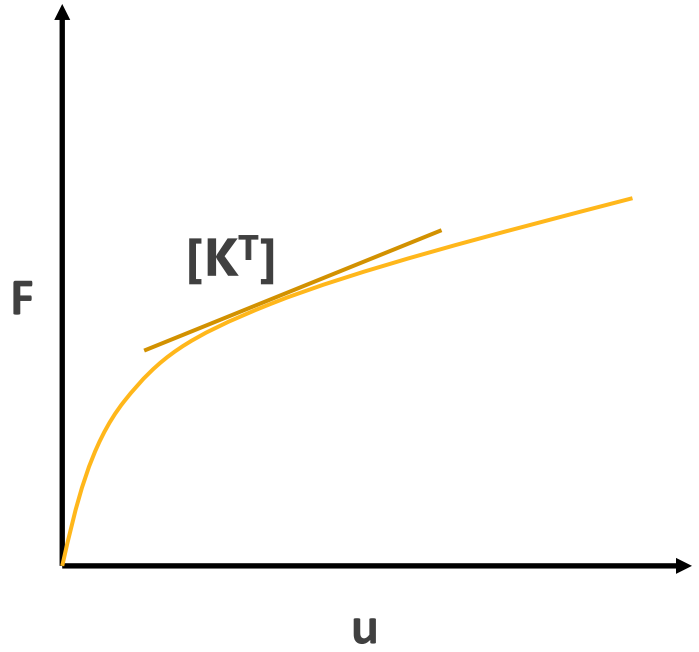


Pre-stress is considered but all other nonlinearities are ignored.

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Modal Analysis Based on Linear Perturbation (cont.)

- If the base analysis is nonlinear, then system stiffness changes with deformation.
- At a given deformation state, the tangent stiffness matrix is calculated and used in LP.
- All nonlinearities are taken into account and “frozen” to calculate the tangent stiffness matrix.

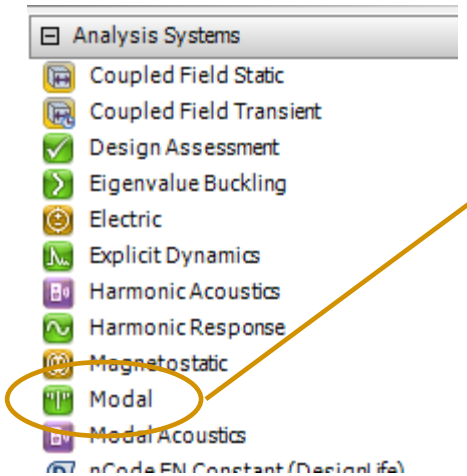


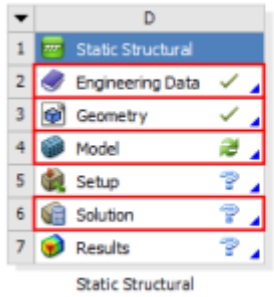
Both pre-stress and other nonlinearities are considered.

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Linear Perturbation Analysis Workflow

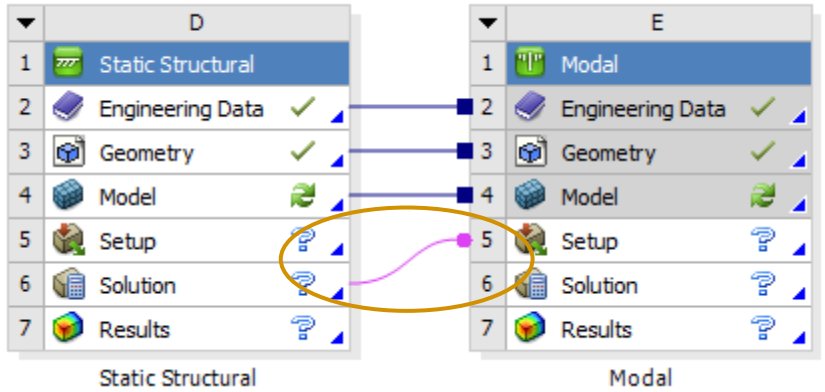
- Establishing a link between base analysis “Solution” and perturb analysis “Setup” prior to solving the Static Structural will ensure that necessary static conditions and restart files are available for the perturbation solution.





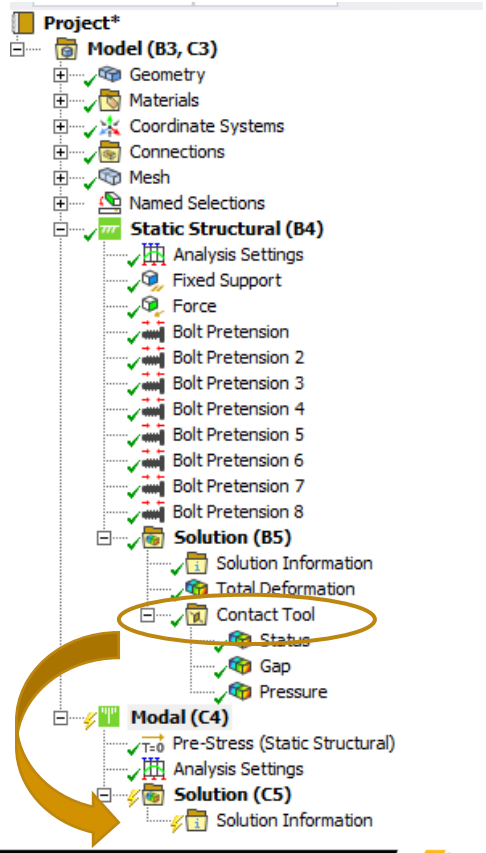


Drag and Drop Modal over Static Structural sharing Engineering Data, Geometry and Model and transferring Solution



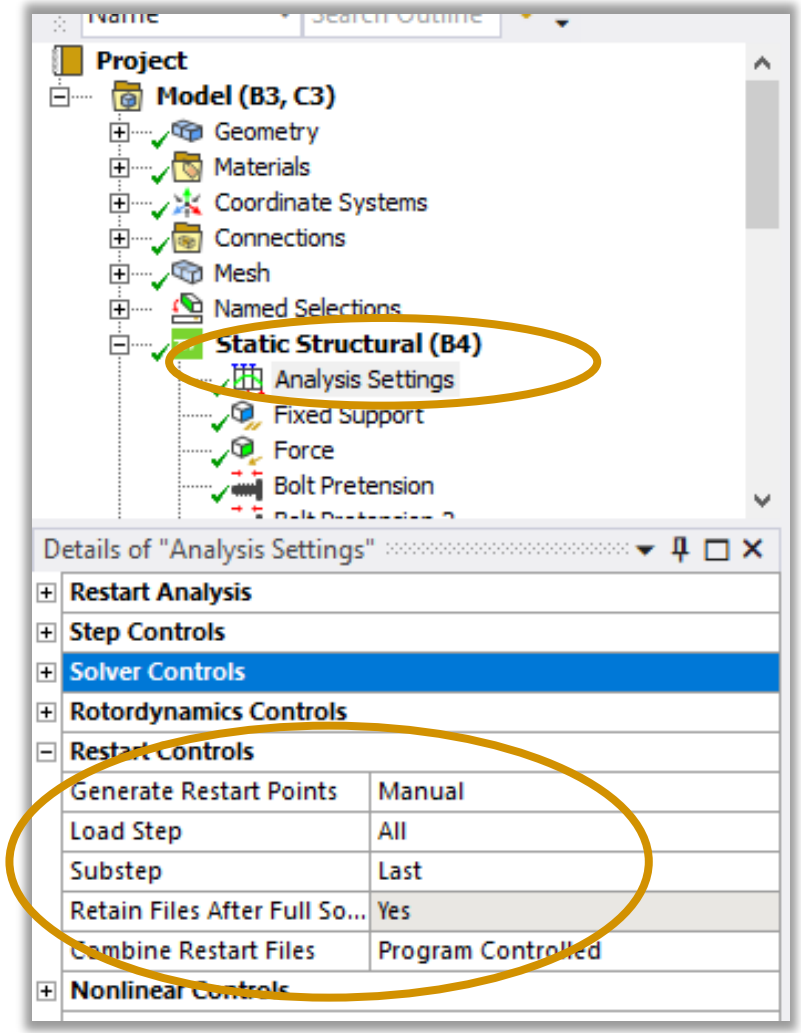
Base analysis

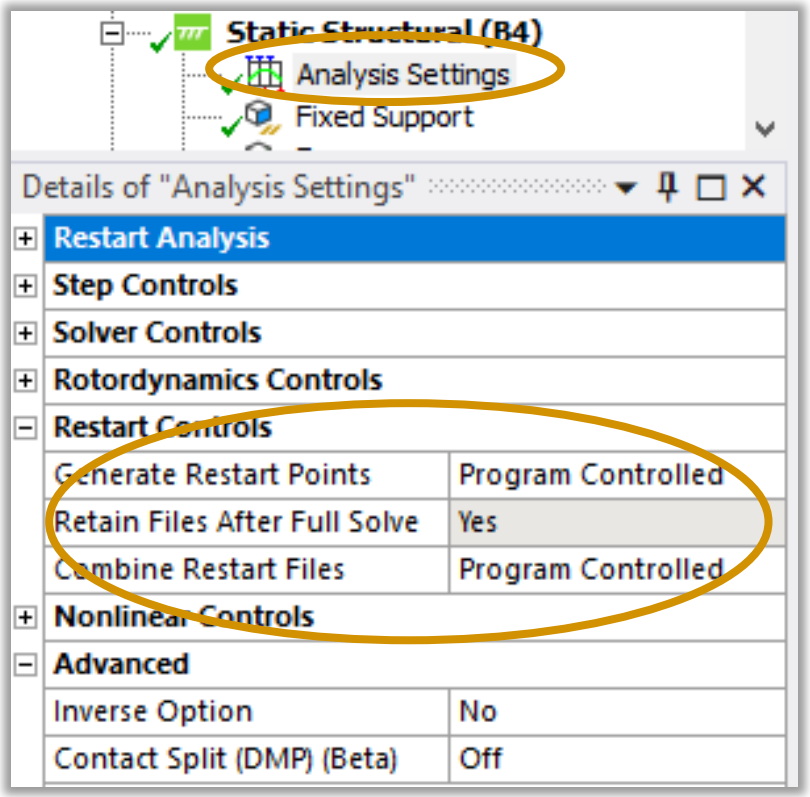
Perturb analysis



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Linear Perturbation Analysis – Modal Analysis Phase 1

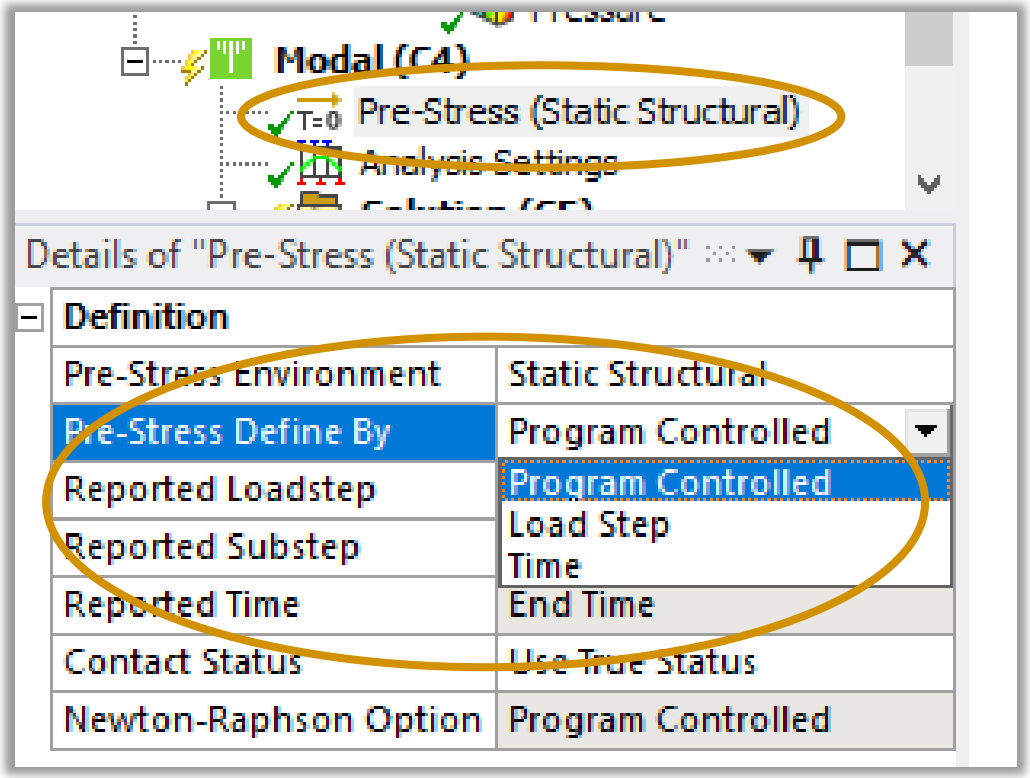




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Linear Perturbation Analysis – Modal Analysis Phase 1 (cont.)

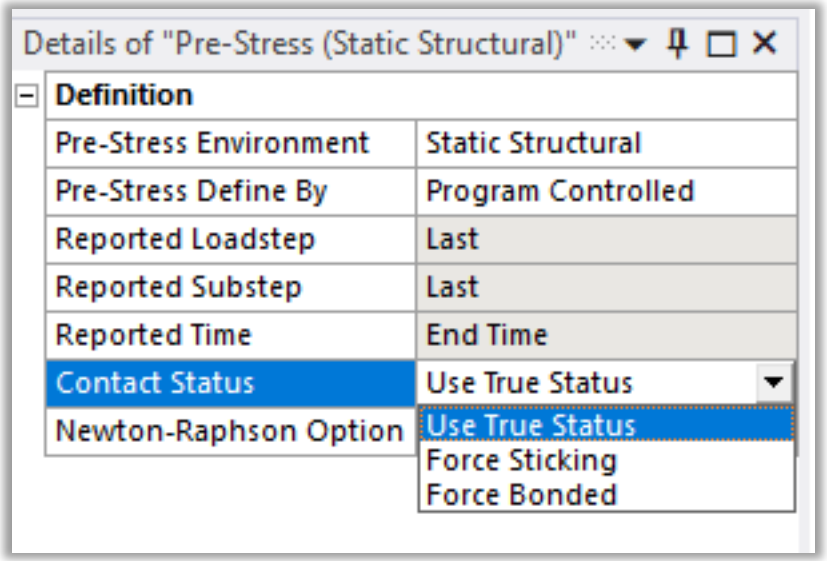
- Any time point from a Static or Transient Structural analysis can be perturbed.



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Linear Perturbation Analysis – Modal Analysis Phase 1 (cont.)

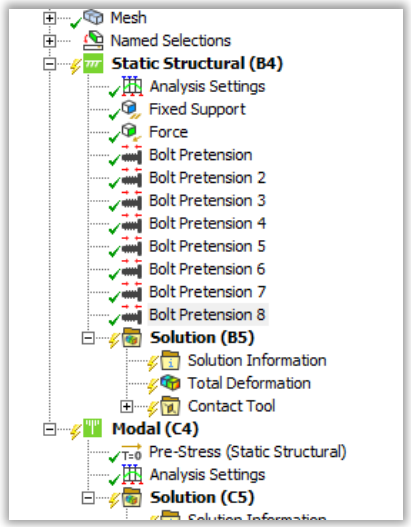
- Contact Status can be:
  - True Status - Uses the current contact status from the restart snapshot. If the previous run for a parent static structural is nonlinear, then the nonlinear contact status at the point of restart is frozen and used throughout the linear perturbation analysis.
  - Force Sticking - Uses sticking contact stiffness for the frictional contact pairs, even when the status is sliding (that is, the “no sliding” status is allowed). This option only applies to contact pairs whose frictional coefficient is greater than zero.
  - Force Bounded - Uses bonded contact stiffness and status for contact pairs that are in the closed (sticking/sliding) state.



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Linear Perturbation Analysis – Modal Analysis Phase 1 (cont.)

- When you link modal analysis to a structural analysis all structural loading conditions are deleted from the base analysis.
- All displacement constraints are kept in conducting the linear perturbation analysis.
- All non-zero displacement constraints are set to zero.



Tabular Data

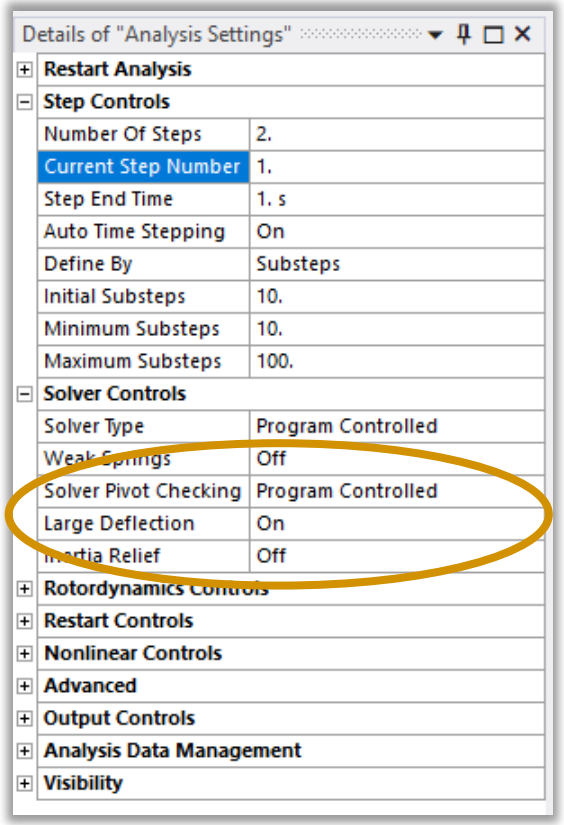
	Steps	Define By	Preload [N]	Preadjustment [mm]	Increment [mm]
1	1.	Load	100.	N/A	N/A
2	2.	Lock	N/A	N/A	N/A
*					

Bolts need to be locked after static structural analysis, otherwise bolt halves may separate in modal analysis.

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Linear Perturbation Analysis – Modal Analysis Phase 2

- Geometry update based on the base analysis. This is done automatically if the large deflection is ON.
- Solve linearly perturbed modal analysis
- Post-process the results
  - Modal results (deformed shape) will be based on the initial geometry from the base analysis.



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