Understanding Dynamic Analysis

SEAWI presentation from Sam Rubenzer of FORSE Consulting

April 27, 2012

my background

- Education
  - University of Minnesota, Bachelors of Civil Engineering
  - Marquette University, Masters of Business Administration
- Experience
  - 7 years of experience as structural engineer in Minneapolis, and Milwaukee
  - 5 years of experience with RAM/Bentley as trainer
  - founded FORSE Consulting in January, 2010
- Licensed
  - Professional Engineer (PE)
  - Structural Engineer (SE)

today's agenda

1. The basics about structural building dynamics
2. Floor Vibration “due to Human Activity”
3. Wind loads and building vibration
4. Low/Moderate Seismic Loads and building vibration

Dynamic Analysis

THE BASICS ABOUT STRUCTURAL BUILDING DYNAMICS

types of dynamic loads on buildings

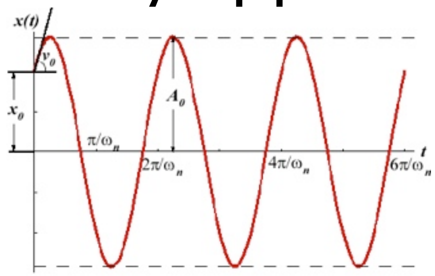
- every structure is subject to dynamic loading.
- dynamic analysis can be used to find:
  - natural frequency
  - dynamic displacements
  - time history results
  - modal analysis

terminology

- **mass** is defined by:
  - mass equals force divided by acceleration, m=f/a
  - mass is also equal to its weight divided by gravity
- **stiffness** of a body is a measure of the resistance offered by an elastic body to deformation.
- **damping** is the resistance to the motion of a vibrating body.
  - there is always some damping present in the system which causes the gradual dissipation of vibration energy and results in gradual decay of amplitude of the free vibration.
  - very little effect on natural frequency of the system,
  - great importance in limiting the amplitude of oscillation at resonance

terminology

- **free vibration** takes place when a system oscillates under the action of forces inherent in the system itself due to initial disturbance, and when the externally applied forces are absent.



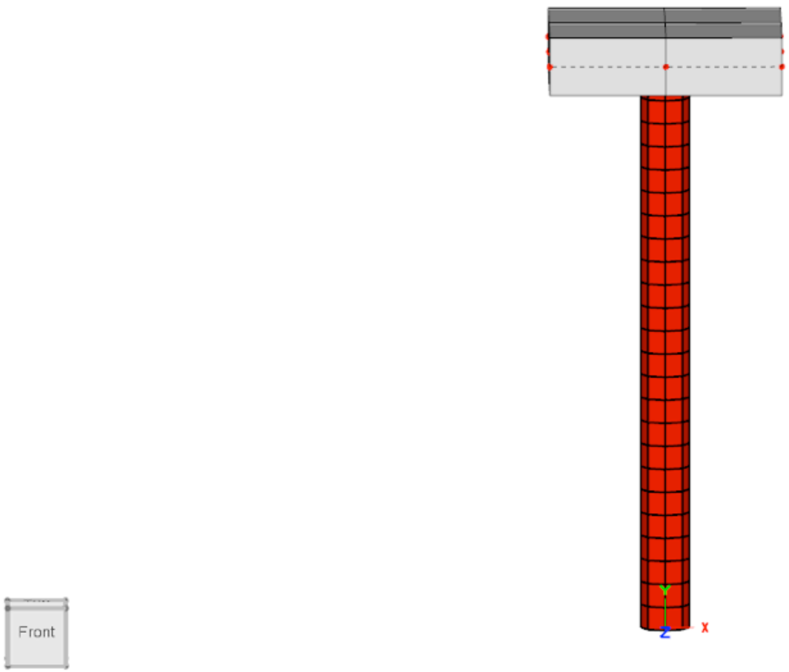
- **frequency** is the number of oscillations completed per unit time
- **amplitude** is the maximum displacement of a vibrating body from its equilibrium position

terminology

- **natural frequency** is the frequency of free vibration of a system
- **simple harmonic motion** is the motion of a body to and fro. The motion is periodic and its acceleration is always directed towards the mean position and is proportional to its distance from mean position

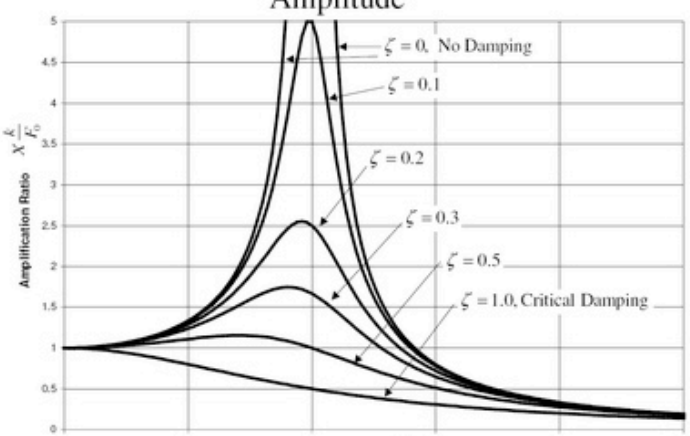
terminology
SDOF – simple harmonic motion

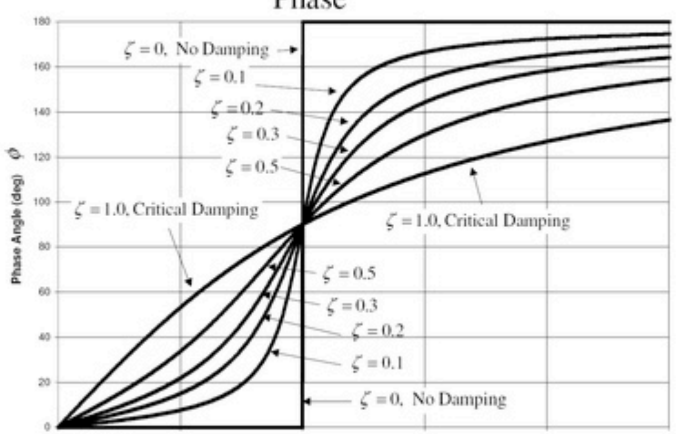
terminology
SDOF – simple harmonic motion



terminology

- **resonance**
  - In a lightly damped system when the forcing frequency nears the natural frequency () the amplitude of the vibration can get extremely high. This phenomenon is called resonance
  - resonance occurs it can lead to eventual failure of the system
  - adding damping can significantly reduce the magnitude of the vibration
  - the magnitude can be reduced if the natural frequency can be shifted away from the forcing frequency by changing the stiffness or mass of the system





terminology

- **degrees of freedom**: The minimum number of independent coordinates needed to describe the motion of a system completely, is called the degree-of-freedom of the system. If only one coordinate is required, then the system is called as single degree-of-freedom system.
- **fundamental mode of vibration** of a system is the mode having the lowest natural frequency

basic equation of motion for elastic single degree of freedom

$$\mathbf{m\ddot{x} + c\dot{x} + kx = p(t)}$$

x = displacement

$\dot{x}$ = velocity

$\ddot{x}$ = acceleration

m = mass

c = damping

k = stiffness

$p(t)$ = external dynamic force

Ref. Anil K. Chopra: Dynamics of Structures, Theory and Applications to Earthquake Engineering, Second Ed.

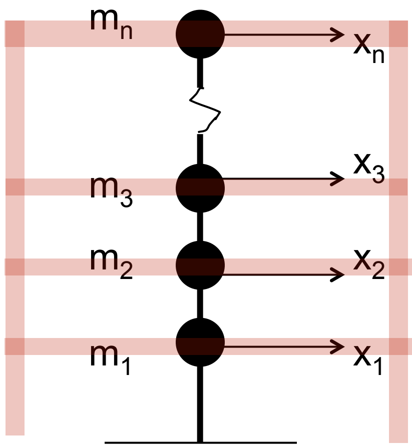
SDOF – simple harmonic motion

- Then since ω = 2πf, $$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$
- and since T = 1/f where T is the time period, $$T = 2\pi\sqrt{\frac{m}{k}}$$
- the period and frequency are independent of the amplitude and the initial phase of the motion

Ref. Anil K. Chopra: Dynamics of Structures, Theory and Applications to Earthquake Engineering, Second Ed.

multiple degree of freedom system (MDOF) shear building

- mdof shear building is approximately stacked sdof systems
- consider a structure consisting of many masses connected together by elements of known stiffness's



- masses move independently with displacements x_1, x_2 … x_n
- majority of the mass is in the floors
- motion is predominantly lateral

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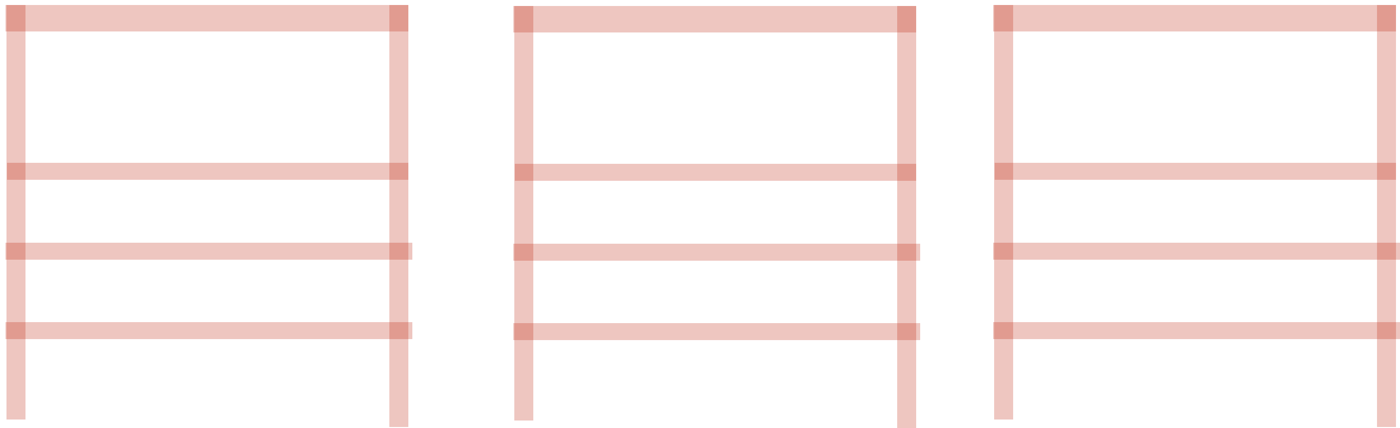
MDOF shear building



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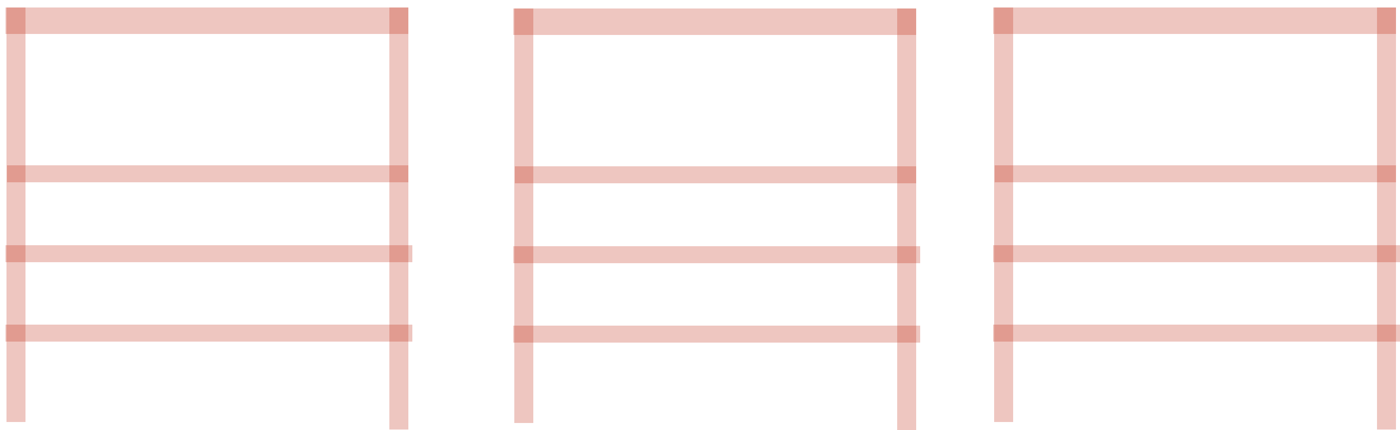
MDOF shear building

Mode shapes:



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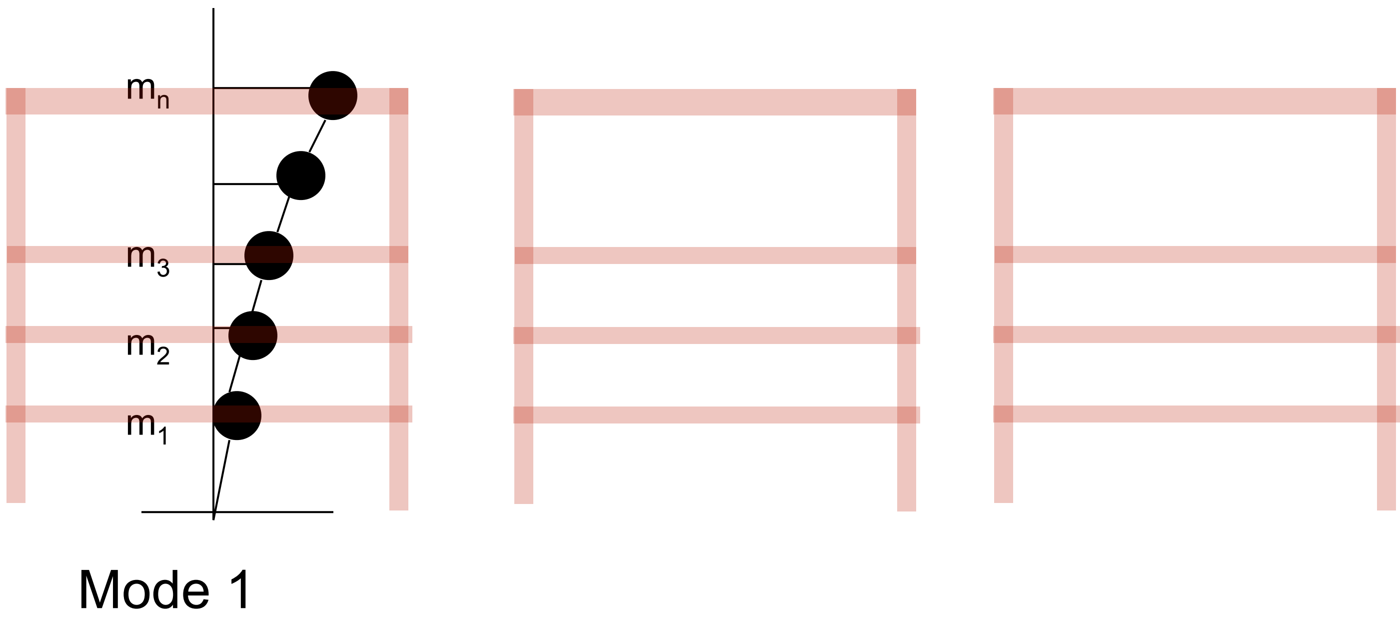

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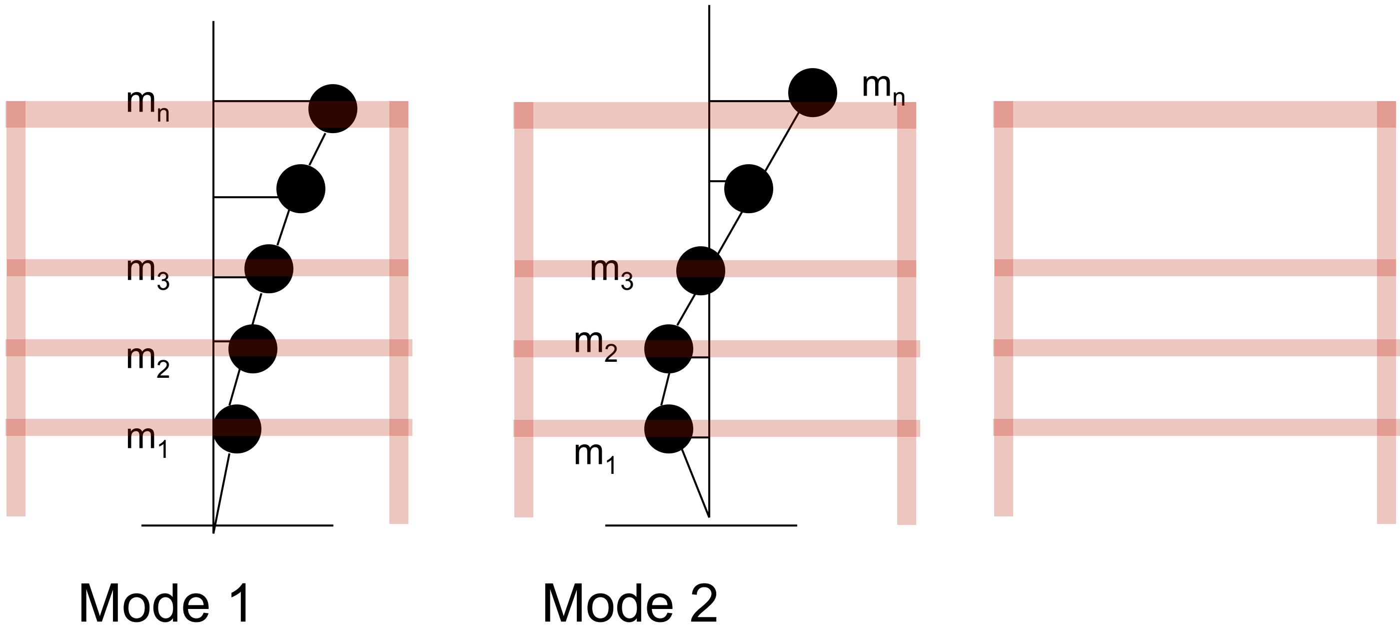

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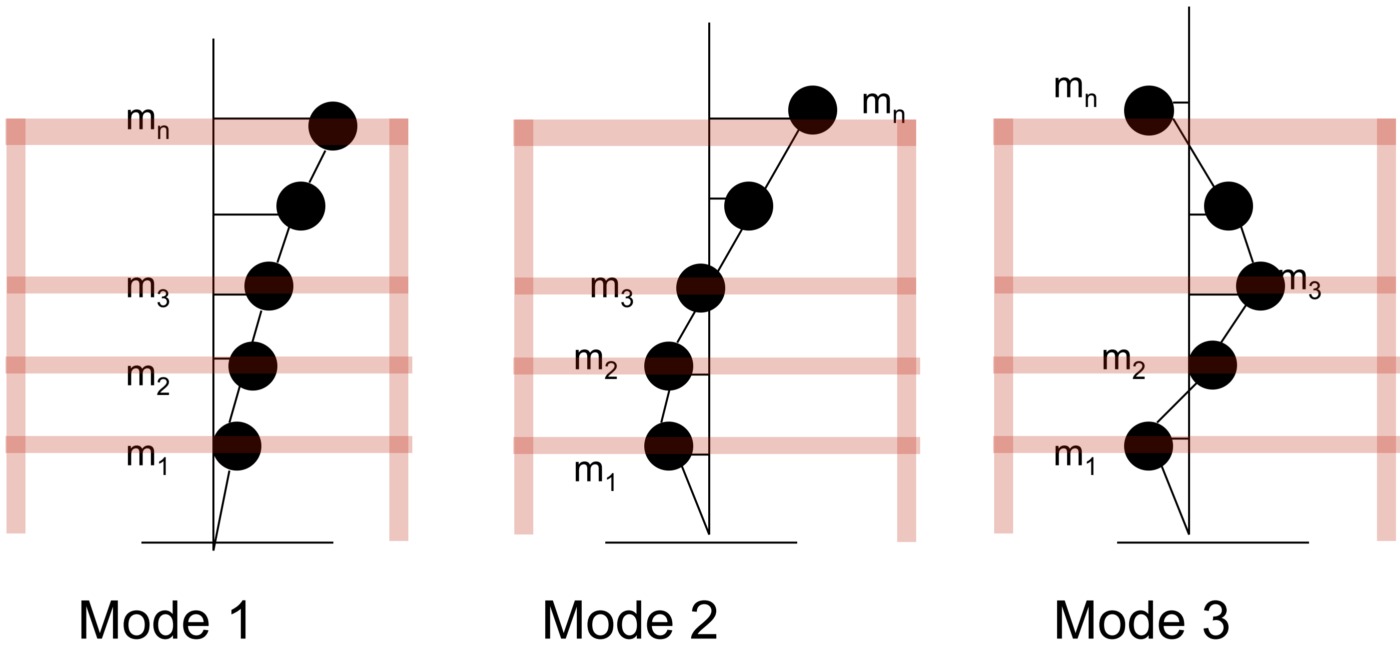

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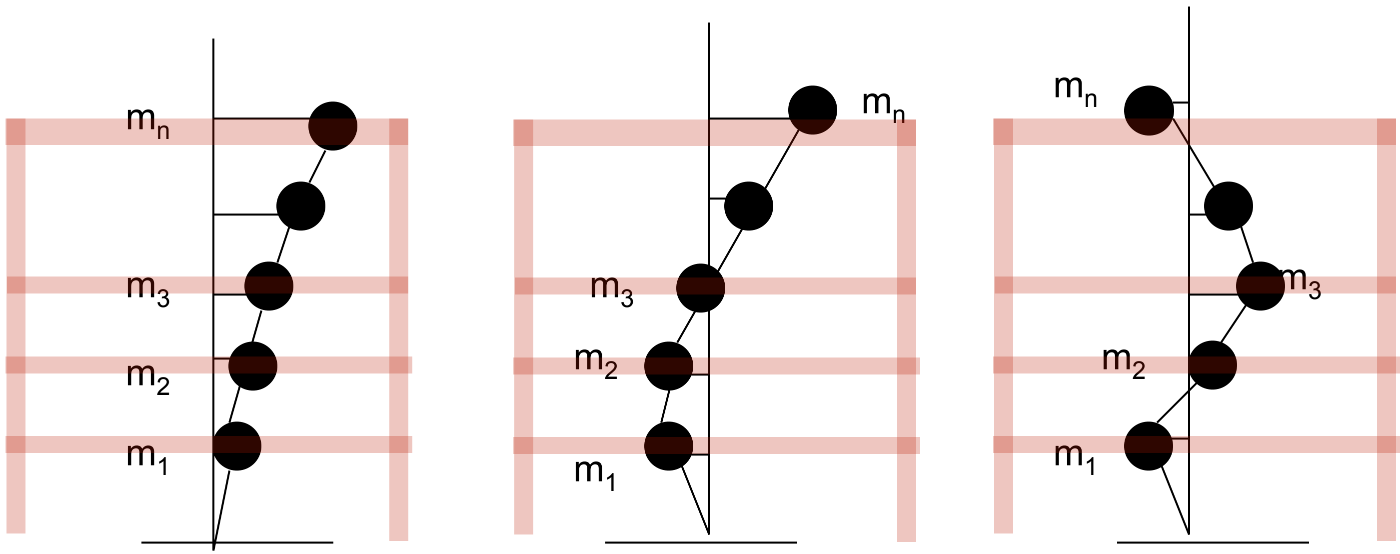

Mode 1 Mode 2 Mode 3

Number of modes, frequencies = number of masses

= degrees of freedom

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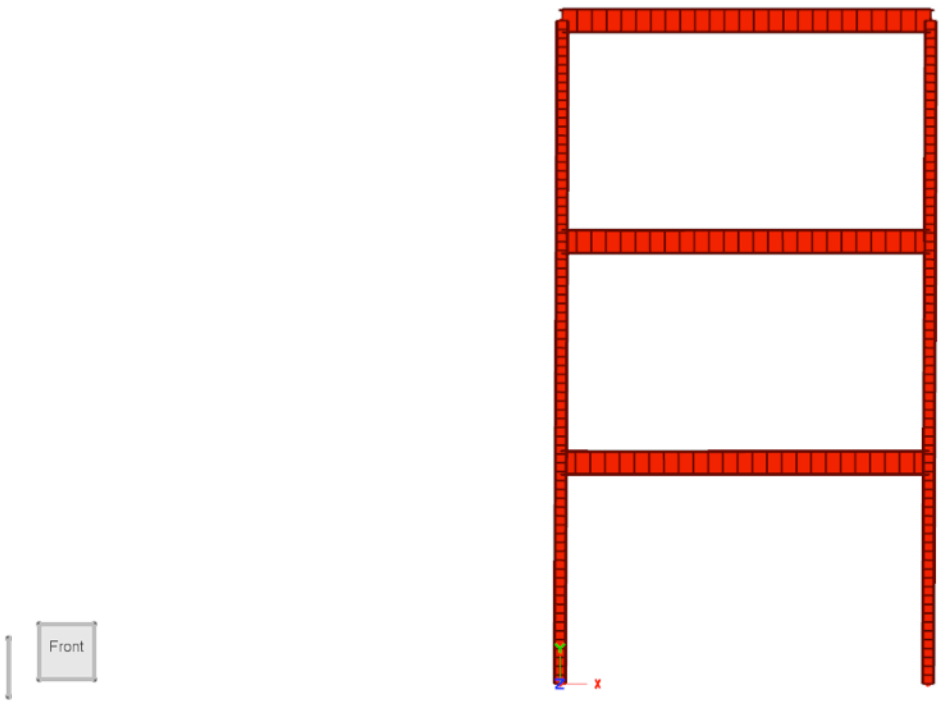
MDOF shear building

MDOF shear building

Mode shapes:



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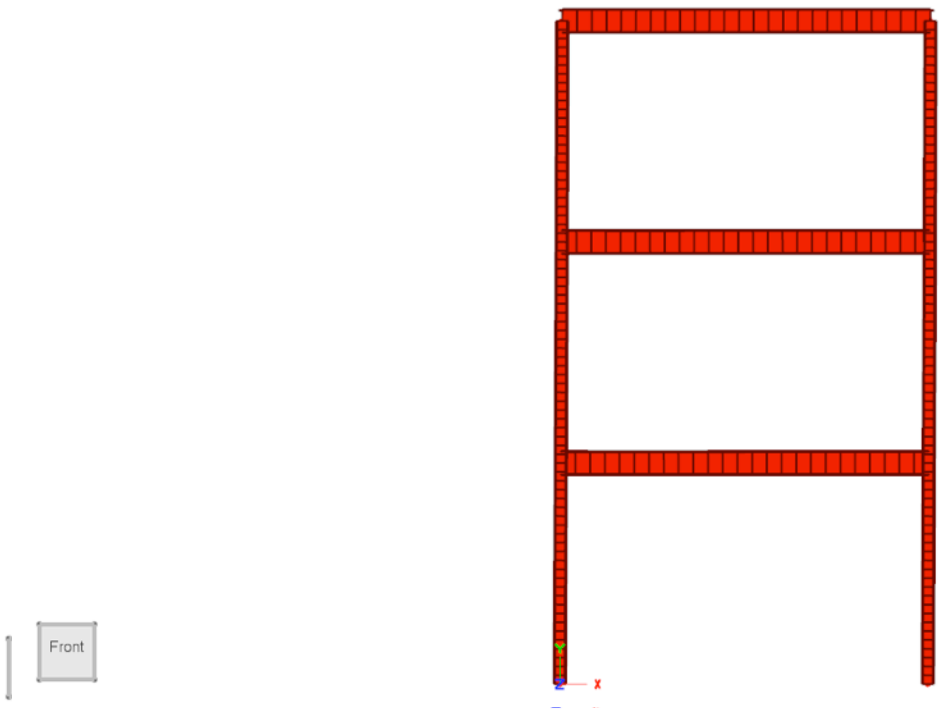
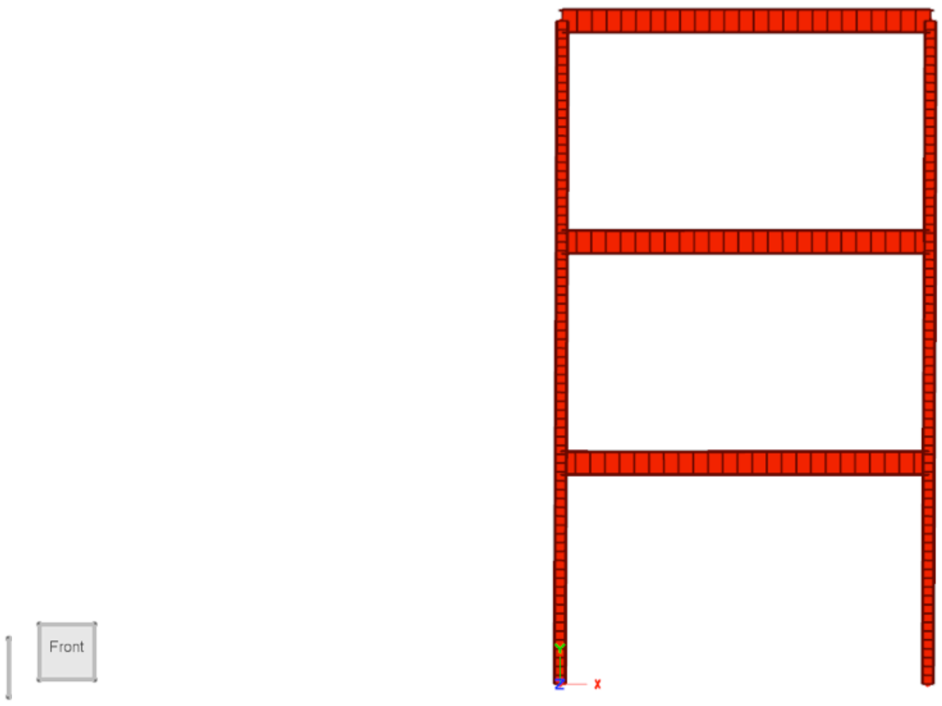


Mode 1

MDOF shear building

Mode shapes:



MDOF shear building

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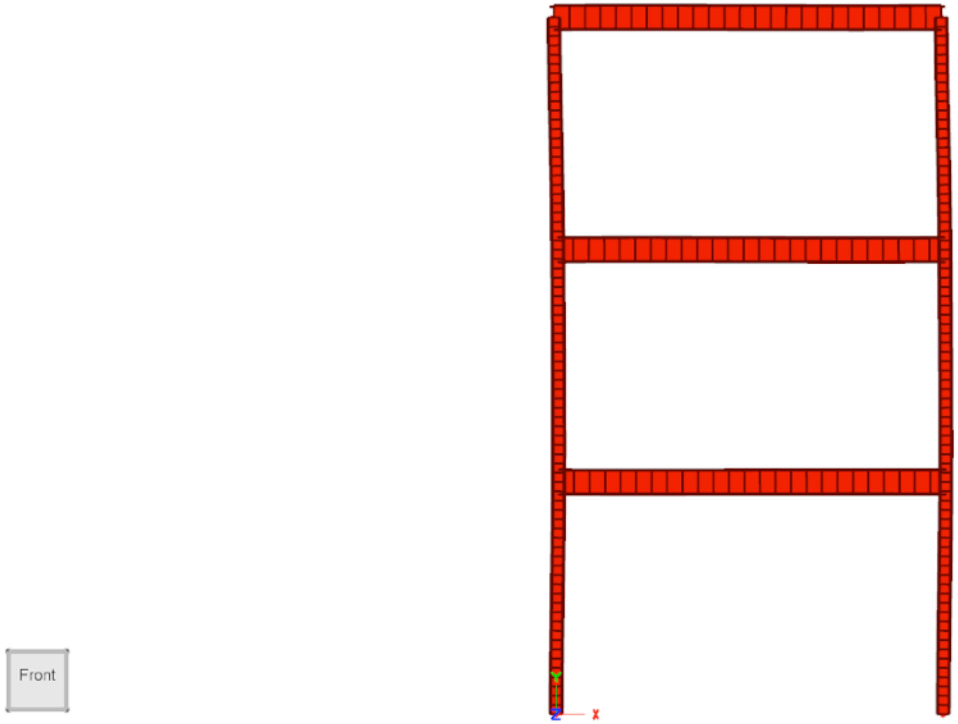


Mode 2

MDOF shear building

Mode shapes:

Mode 2

MDOF systems

- Generally, the first mode of vibration is the one of primary interest.
  - usually has the largest contribution to the structure's motion
  - period of this mode is the longest
    - shortest natural frequency and first eigenvector

Ref. Anil K. Chopra: Dynamics of Structures, Theory and Applications to Earthquake Engineering, Second Ed.

MDOF systems

- significance of a mode is indicated by Mass Participation
  - factor indicates the amount of the total structural mass that is activated by a single mode
  - if all modes of a structure are considered, the cumulative Mass Participation will be 100%
  - this idea of mass participation also helps us
    - we don’t have to solve ALL the mode shapes
    - codes allow us to capture 80-90% of mass
    - keeps analysis more reasonable
  - participation factors are used in most commercial software packages and generally defined as mass participation %

Ref. Anil K. Chopra: Dynamics of Structures, Theory and Applications to Earthquake Engineering, Second Ed.

DYNAMIC ANALYSIS

NATURAL FREQUENCY

natural frequency

- fundamental building period is simply the inverse of the building frequency at the lowest harmonic
- Basically, every system has a set of frequencies in which it "wants" to vibrate when set in motion by some sort of disturbance based on the system's mass and stiffness characteristics.
- The shortest frequency is known as the natural frequency
- The inverse of frequency is the period of the system, and more specifically, the inverse of the natural frequency is the fundamental period

natural frequency for floor vibrations

- here we are concerned with the vibration of the entire floor area, not single members and not entire buildings
  - beam frequency
  - girder frequency
  - combined mode properties to determine the “fundamental floor frequency”

natural frequency for wind

- concerned with the vibration of lateral wind resisting system
- in wind design
  - longer fundamental periods are indicative of buildings that are more susceptible to dynamic amplification effects from sustained wind gusts
  - result in higher design forces.

natural frequency for seismic

- in seismic design
  - the closer the frequency of an earthquake is to the natural frequency of a building, the more energy is introduced into the building structure
  - buildings with shorter fundamental periods attract higher seismic forces as the code-based design spectrum exhibits higher accelerations at shorter periods.

first step in dynamic analysis

- In order to investigate the magnitudes of these floor, wind and seismic effects, the fundamental periods of the area affected must first be determined

Dynamic Analysis

FLOOR VIBRATION

dynamic analysis for steel floor vibrations

- based on AISC Design Guide 11: Floor Vibrations Due to Human Activity
- fairly straight forward analysis which we can calculate manually, or with simple software
- in the presentation today, we'll use:
  - Excel spreadsheets
  - Fastrak Building Designer
  - Floorvibe
  - RISA Floor

dynamic analysis for steel floor vibrations

- most floor vibration problems involve:
  - repeated forces caused by machinery
  - human activities:
    - dancing
    - aerobics
    - walking
- in some cases, the applied force is sinusoidal or similar
- in general, a repeated force can be represented by a combination of sinusoidal forces whose frequencies, f, are multiples or harmonics of the basic frequency of the force repetition, e.g. step frequency, f_{step}, for human activities

dynamic analysis for steel floor vibrations

- the natural frequency of almost all concrete slab structural steel supported floors can be close to or can match a harmonic forcing frequency of human activities
  - resonance amplification is associated with most of the vibration problems that occur in buildings using structural steel
- there are likely many modes of vibration in a floor system.
- each mode of vibration has its own displacement configuration or "mode shape" and associated natural frequency
- in practice, the vibrational motion of building floors are localized to one or two panels, because of the constraining effect of multiple column/wall supports and non-structural components, such as partitions

AISC Design Guide 11: Floor Vibrations Due to Human Activity

dynamic analysis for steel floor vibrations

- walking generates a concentrated force
  - may excite a higher mode
  - it is usually only the lowest modes of vibration that are of concern for human activities
- the response factor depends strongly on:
  - the ratio of natural frequency to forcing frequency
  - vibration at or close to resonance, on the damping ratio
    - it is these parameters that control the vibration serviceability design of most steel floor structures
- it is possible to control the acceleration at resonance by increasing damping or mass

first step in dynamic analysis – fundamental period

- for an individual beam:

$$f_n = \frac{\pi}{2}\left[\frac{gE_sI_t}{wL^4}\right]^{1/2}$$

- for the combined mode of the system, we can approximate using the Dunkerley relationship:

$$\frac{1}{f_n^2} = \frac{1}{f_j^2} + \frac{1}{f_g^2}$$

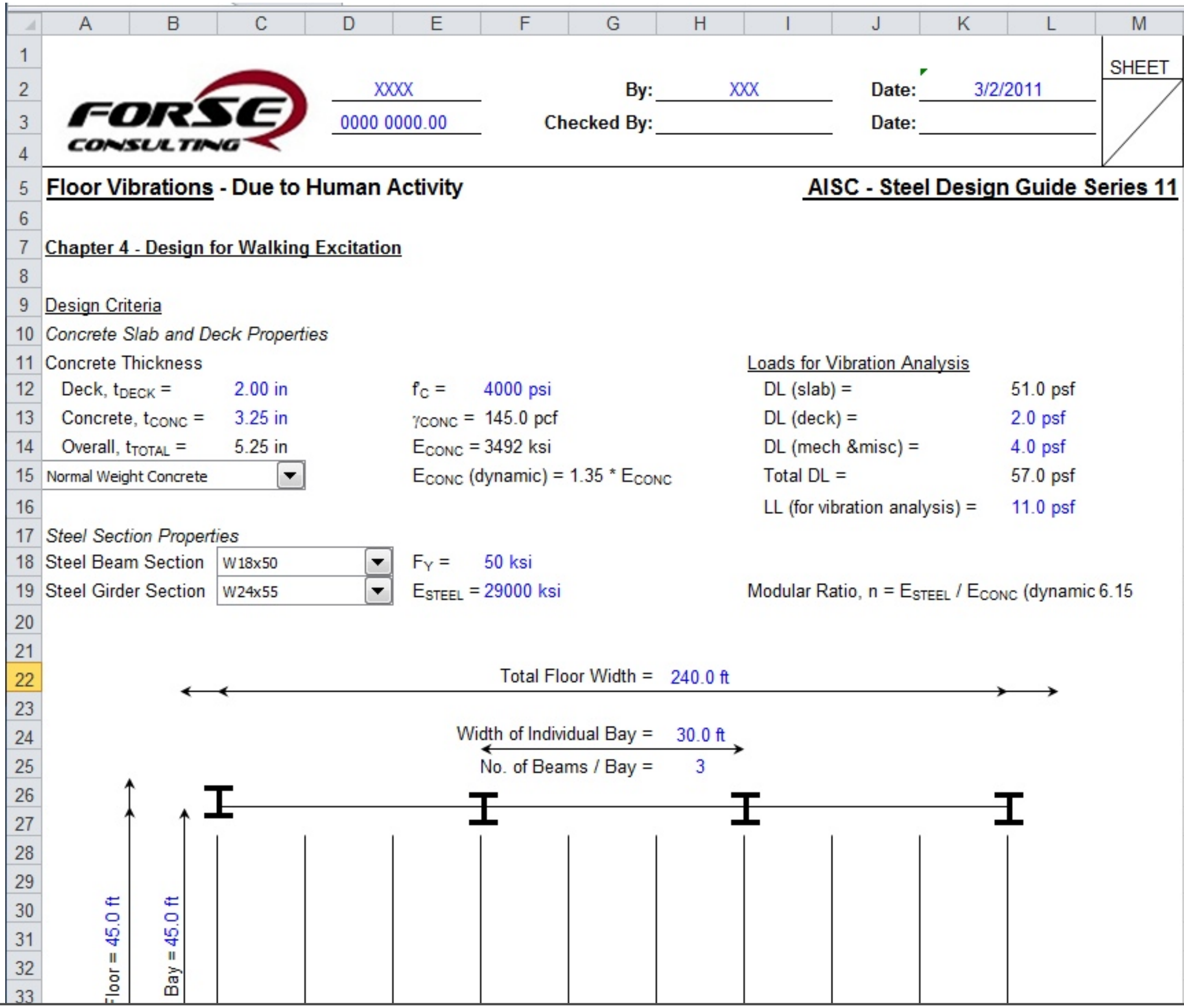
- which can be rewritten as:

$$f_n = 0.18\sqrt{\frac{g}{(\Delta_j + \Delta_g)}}$$

first step in dynamic analysis – fundamental period

- Also need to consider:
  - composite action
  - continuity (continuous beam action)
  - deflection due to shear
  - cantilevers
  - joists and joist girder behavior
  - damping

dynamic analysis for steel floor vibrations – simple software solution



dynamic analysis for steel floor vibrations – simple software solution

Combined Mode Properties

If L_G is less than B_J, the combined mode is restricted and the system is effectively stiffened.

$\Delta_G = (L_G / B_J) * \Delta_G'$ 0.186 in

Otherwise

$\Delta_G = \Delta_G' =$ N/A

Floor Fundamental Frequency

$f_N = 0.18 * \sqrt{(g / (\Delta_J + \Delta_G))} =$ 3.49 Hz

Effective Panel Mode Panel Weight

$W = \Delta_J / (\Delta_J + \Delta_G) * W_J + \Delta_G / (\Delta_G + \Delta_J) * W_G =$ 124.0 k

$\Delta_J / (\Delta_J + \Delta_G) * W_J =$ 111.70 k

$\Delta_G / (\Delta_G + \Delta_J) * W_G =$ 12.29 k

Indicate the appropriate occupancy by selecting from the categories below:

Offices, Residences, and Churches with non-structural components and furnishings

Use the following Parameters from Table 4.1

Constant Force, $P_0 =$ 65.0 lb

Damping Ratio, $\beta =$ 0.03

Acceleration Limit, $a_0/g =$ 0.50% of g

Floor Fundamental Natural Frequency

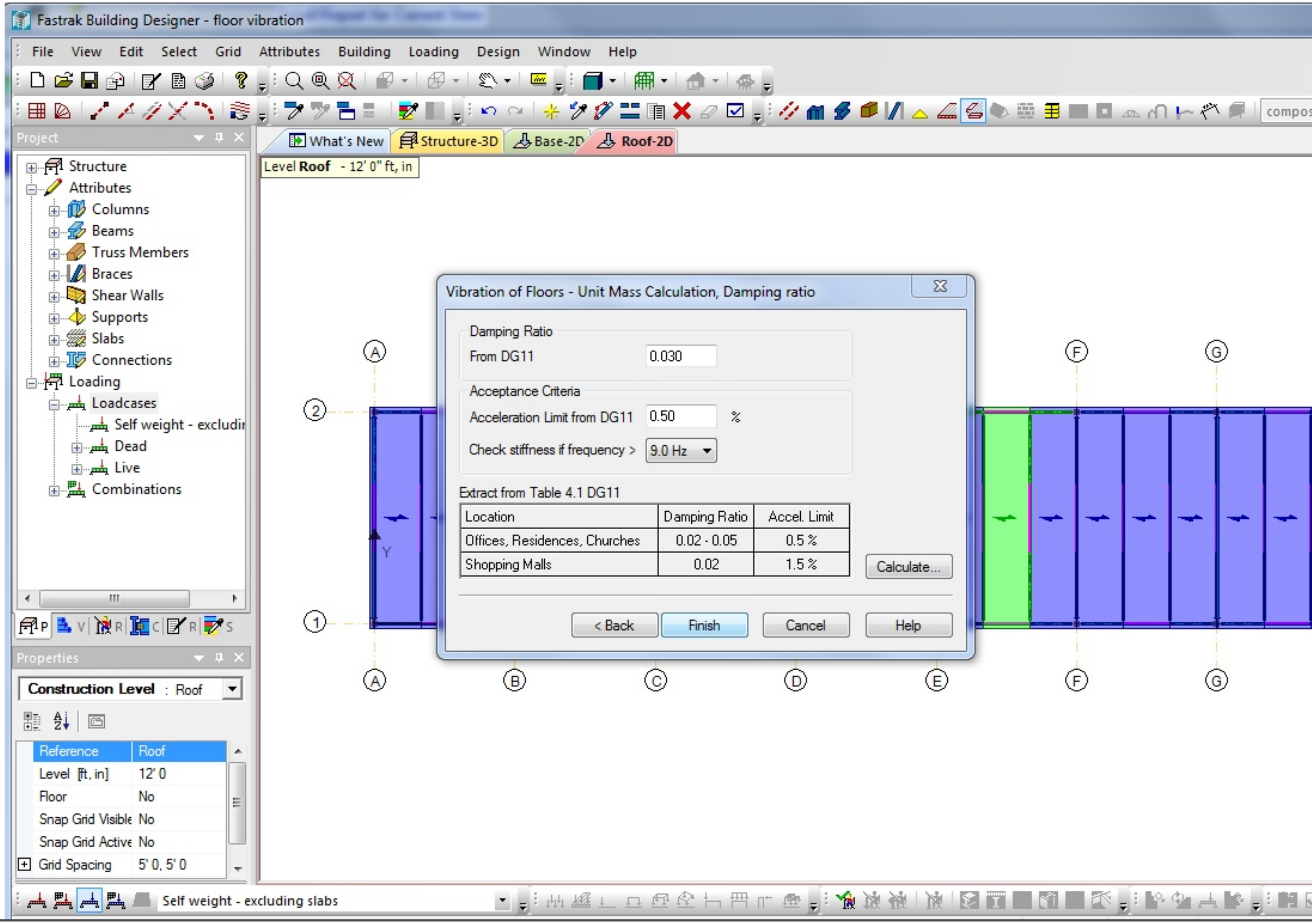
$a_P/g = P_0 * \exp(-0.35 * f_N) / (\beta * W)$

Individual Beam $a_B/g =$ **0.41% of g** OK, <0.5% of g

Individual Girder $a_G/g =$ **0.28% of g** OK, <0.5% of g

Combined Panel $a_P/g =$ **0.52% of g** NG, >0.5% of g

dynamic analysis for steel floor vibrations – simple software solution



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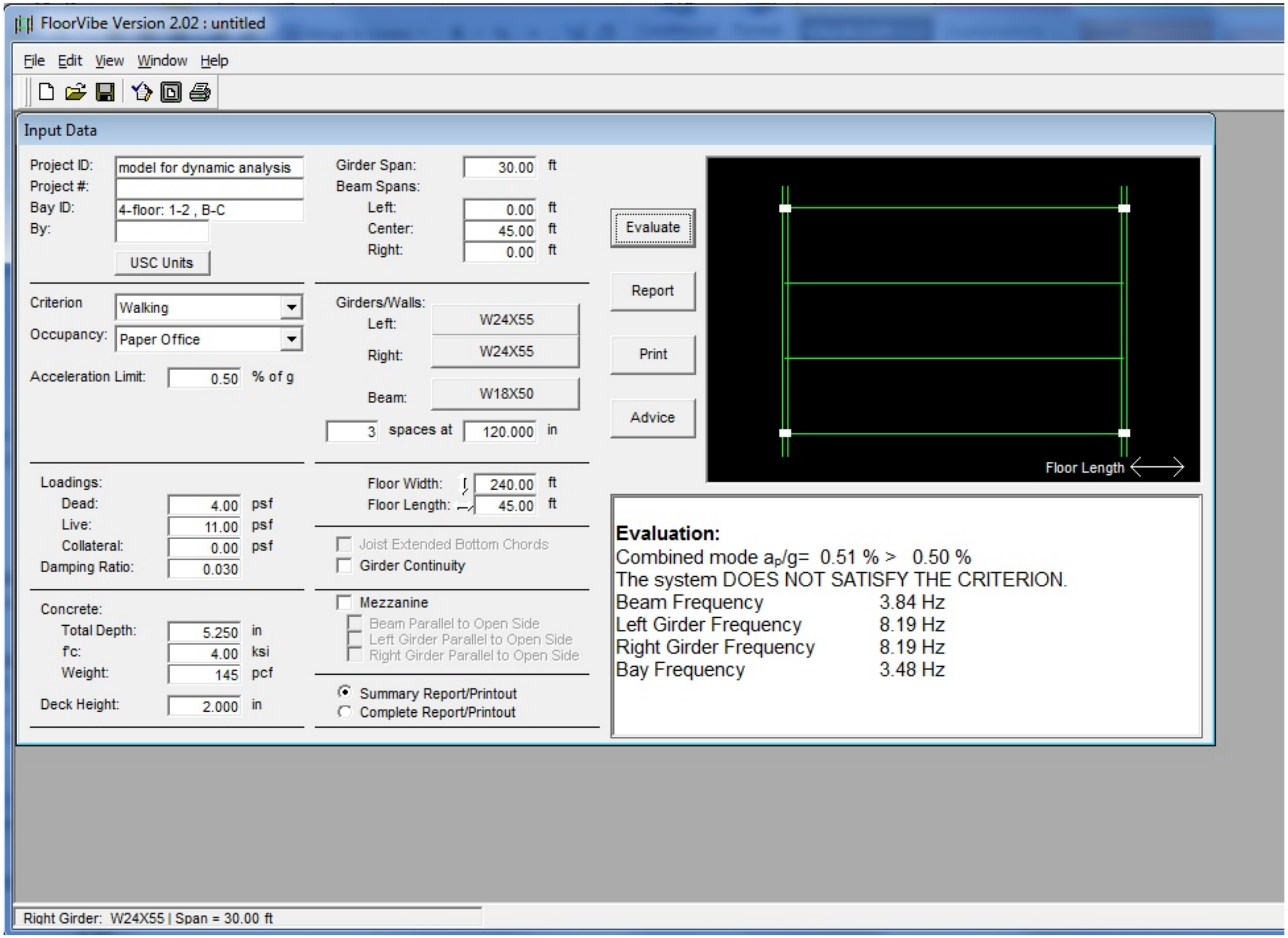
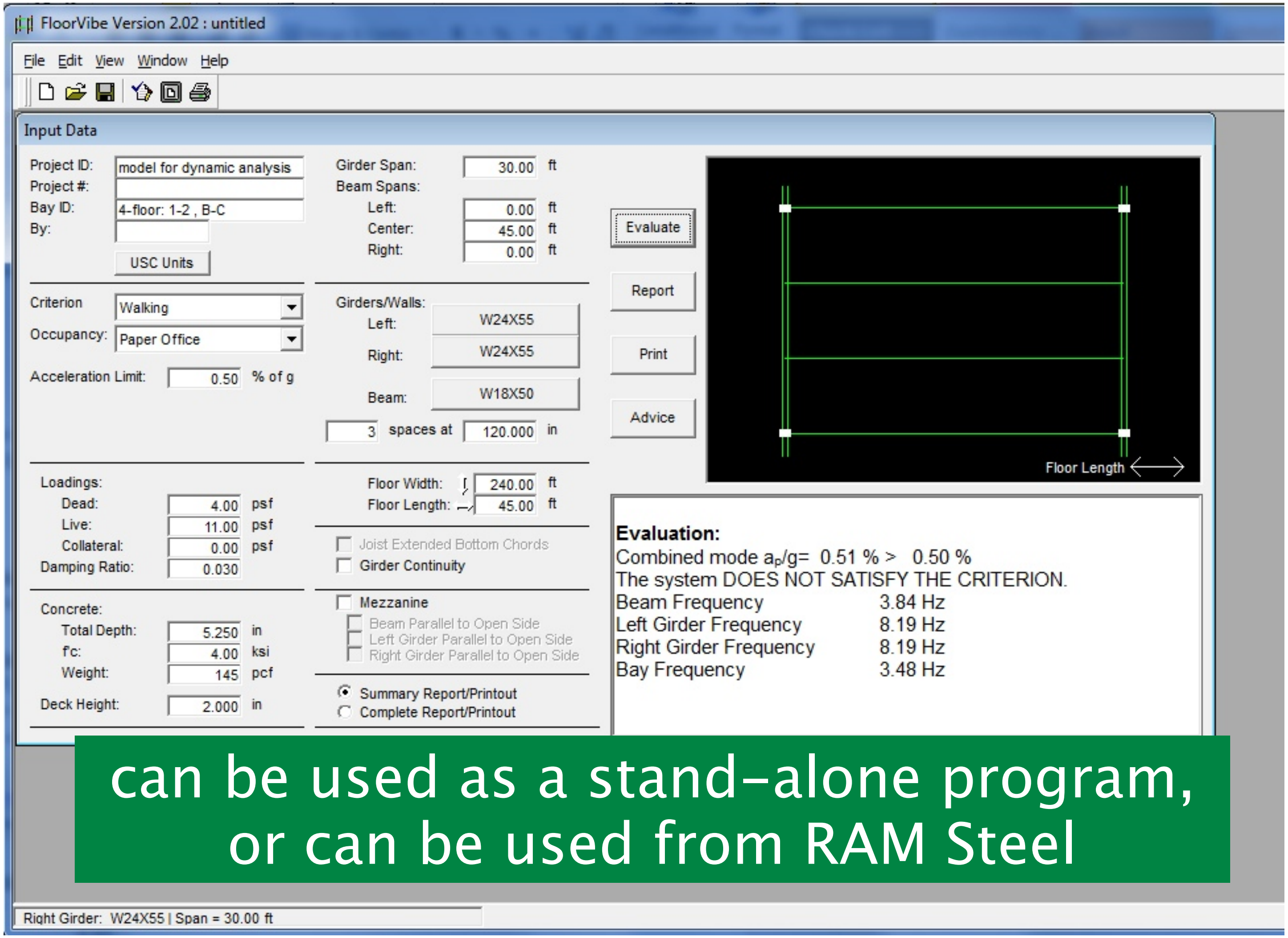
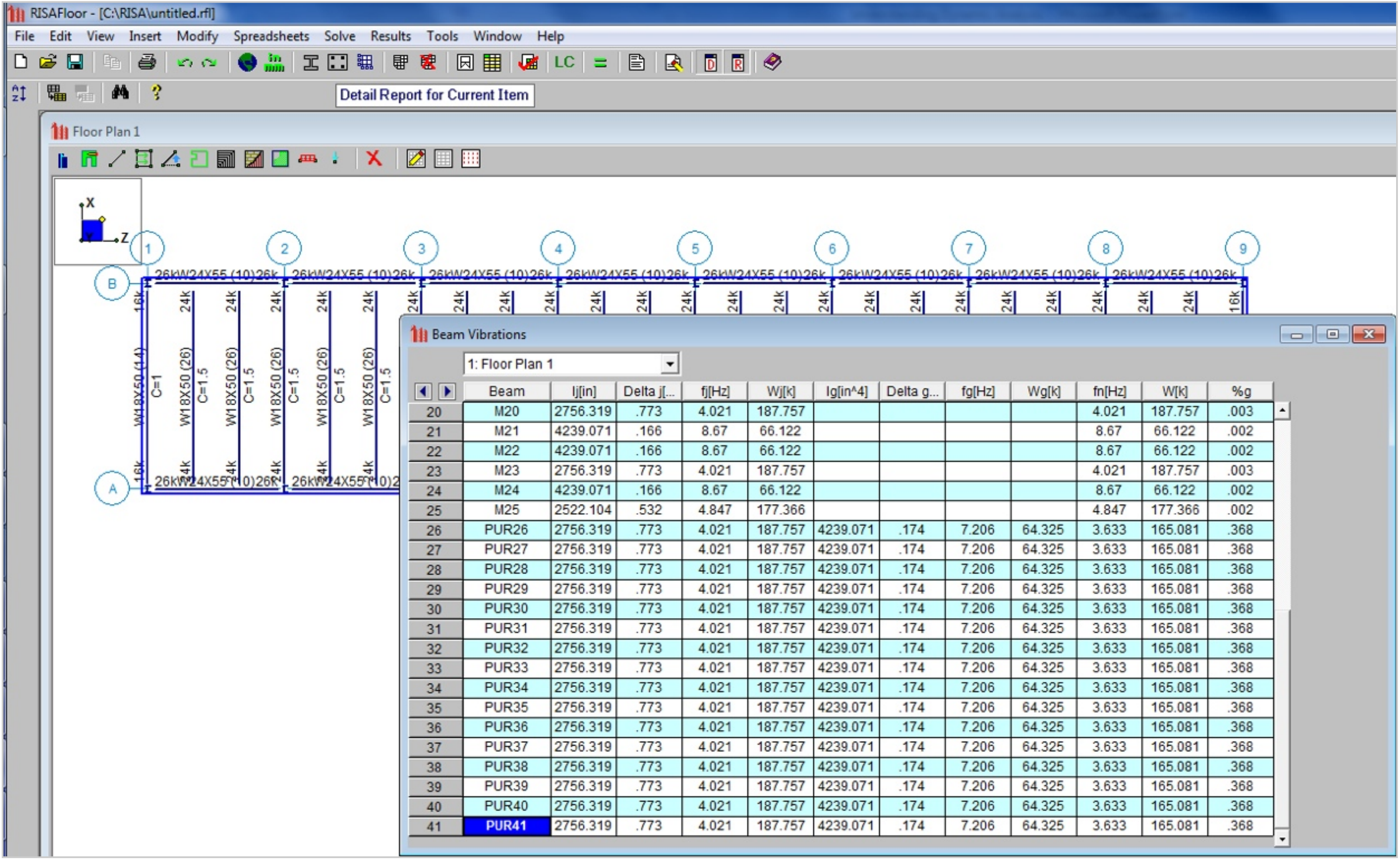


dynamic analysis for steel floor vibrations – simple software solution



can be used as a stand-alone program, or can be used from RAM Steel

dynamic analysis for steel floor vibrations – simple software solution



	Beam	Ij[in]	Delta j[...	fj[Hz]	Wj[k]	Ig[in^4]	Delta g...	fg[Hz]	Wg[k]	fn[Hz]	W[k]	%g
20	M20	2756.319	.773	4.021	187.757					4.021	187.757	.003
21	M21	4239.071	.166	8.67	66.122					8.67	66.122	.002
22	M22	4239.071	.166	8.67	66.122					8.67	66.122	.002
23	M23	2756.319	.773	4.021	187.757					4.021	187.757	.003
24	M24	4239.071	.166	8.67	66.122					8.67	66.122	.002
25	M25	2522.104	.532	4.847	177.366					4.847	177.366	.002
26	PUR26	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
27	PUR27	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
28	PUR28	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
29	PUR29	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
30	PUR30	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
31	PUR31	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
32	PUR32	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
33	PUR33	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
34	PUR34	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
35	PUR35	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
36	PUR36	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
37	PUR37	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
38	PUR38	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
39	PUR39	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
40	PUR40	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368
41	PUR41	2756.319	.773	4.021	187.757	4239.071	.174	7.206	64.325	3.633	165.081	.368

Dynamic Analysis

WIND LOADS AND BUILDING VIBRATION

use approximate methods for wind periods

- fundamental building period for seismic design calculations is well established
- parameters used for wind design have traditionally not been as clear
- For wind design, the building period is only relevant for those buildings designated as "flexible
  - the fundamental building period is introduced into the gust-effect factor, Gf, in the form of the building natural frequency
- what building period should be used?
- designers typically used:
  - either the approximate equations within the seismic section
  - values provided by an automated eigenvalue analysis

Ref. William P. Jacobs, V, P.E.: STRUCTURE Magazine (June 2008); Building Periods: Moving Forward (and Backward)

code allows us to use modified gust factor

- wind affects buildings dynamically with long periods, short frequencies
  - further study is required for buildings with a frequency of less then 1 hertz (more than 1 sec period) will be affected
    - code requires modifications to the gust factor
  - for rigid buildings, the code allows use to essentially ignore dynamic wind effects

code allows us to use modified gust factor

- Rigid buildings
  - building whose fundamental frequency is greater than or equal to 1 hertz (ASCE 7-05, ASCE 7-10)
  - all Low Rise Buildings (ASCE 7-10, Section 26.9.2)
    - buildings with mean roof height less than or equal to 60ft
    - mean roof height does not exceed least horizontal dimension
  - code allows to use G = 0.85
    - still the case in ASCE 7-10
  - or more complex option, $G = 0.925\left(\frac{1+1.7g_Q I_{\bar{z}} Q}{1+1.7g_V I_{\bar{z}}}\right)$, based on:
    - building size
    - exposure characteristics
    - not dependent on dynamic characteristics

ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures

considering dynamic effects – approximate periods

- <u>approximate seismic equations are intentionally skewed towards shorter building periods</u>
- for wind design, where longer periods equate to higher base shears, their use can provide potentially **<u>un-conservative</u>** results
- results of an eigenvalue analysis can yield building periods much longer than those observed in actual tests, thus providing potentially **<u>overly conservative</u>** results
- ASCE 7-10 presents recommendations for building natural frequencies to be used for wind design
  - for buildings less than 300ft
  - building height is less than 4 times its effective length

Ref. William P. Jacobs, V, P.E.: STRUCTURE Magazine (June 2008); Building Periods: Moving Forward (and Backward)

considering dynamic effects – approximate periods

- ASCE 7-10 recommendations for approximate natural frequencies
  - structural steel moment resisting frame
    - $n_a = 22.2/h^{0.8}$
  - concrete moment resisting frame
    - $n_a = 43.5/h^{0.9}$
  - structural steel and concrete buildings with other lateral force resisting systems
    - $n_a = 75/h$
  - concrete or masonry shearwalls
    - $n_a = 385*C_w^{0.5}/h$

ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures

dynamically sensitive buildings

- ASCE 7 presents a complex set of equations to rationalize a dynamic problem to a static problem
- largely dependent on building periods (calculated or approximated)
- be careful….!

dynamic analysis for wind

- dynamic analysis for simple structures can be carried out manually
- for complex structures finite element analysis can be used to calculate the mode shapes and frequencies

performing a dynamic analysis simulated wind histories

- turbulent wind speed histories can be used to conduct a dynamic analysis
  - more common for:
    - non building structures, sign supports
    - very tall buildings

Ref. Professor Christopher M. Foley, Ph.D: Marquette University; class notes from "Structural Engineering for Natural Hazards Mitigation"

performing a dynamic analysis considering damping

- damping is any effect that reduces the amplitude of vibrations
- for buildings, damping results from many conditions:
  - presence of interior partition walls
  - steel plastic hinging
  - concrete cracking
  - engineered damping devices
- damping values used for wind design are much lower as buildings subject to wind loads are generally responding within the elastic range
- Again, the ASCE 7-10 Commentary provides guidance, suggesting:
  - one percent be used for steel buildings
  - two percent be used for concrete buildings
  - these wind damping values are typically associated with determining wind loads for serviceability
    - "because the level of structural response in the serviceability and survivability states is different, the damping values associated with these states may differ."

Ref. William P. Jacobs, V, P.E.: STRUCTURE Magazine (June 2008); Building Periods: Moving Forward (and Backward)

performing a dynamic analysis consider damping

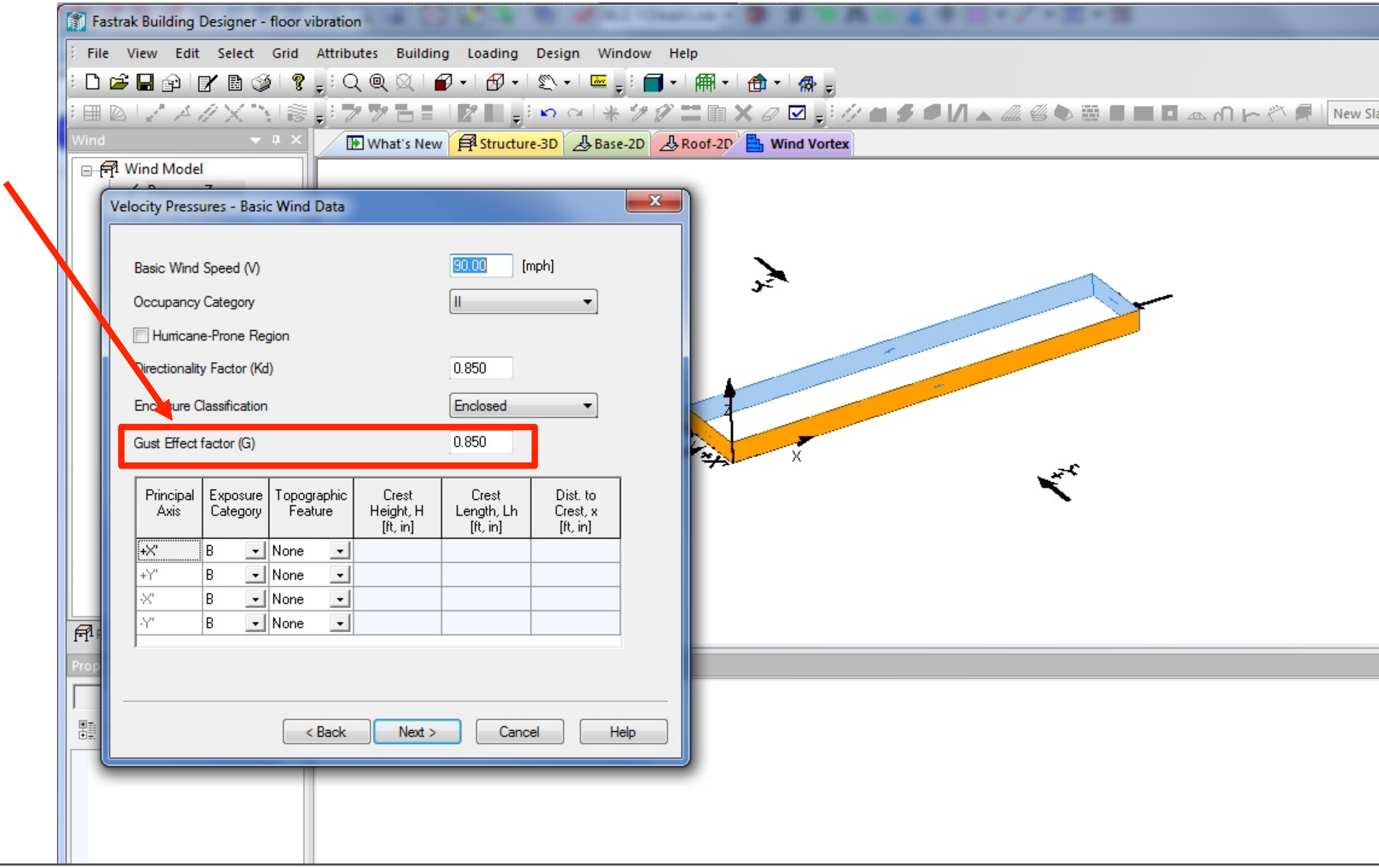
- first, as buildings are subjected to ultimate level forces
  - severe cracking of concrete sections and plastic hinging of steel sections have the dual effect:
    - increasing damping
    - softening the building and increasing the fundamental building period
  - increase in damping and period generally compensate each other, and adequate results can be obtained by utilizing factored forces based on service level periods and damping values.
- second, the level of damping has only a minor effect on the overall base shear for wind design for a large majority of low and mid-rise building structures
  - where serviceability criteria govern, such as accelerations for tall buildings, a more in-depth study of damping criteria is typically warranted

Ref. William P. Jacobs, V, P.E.: STRUCTURE Magazine (June 2008); Building Periods: Moving Forward (and Backward)

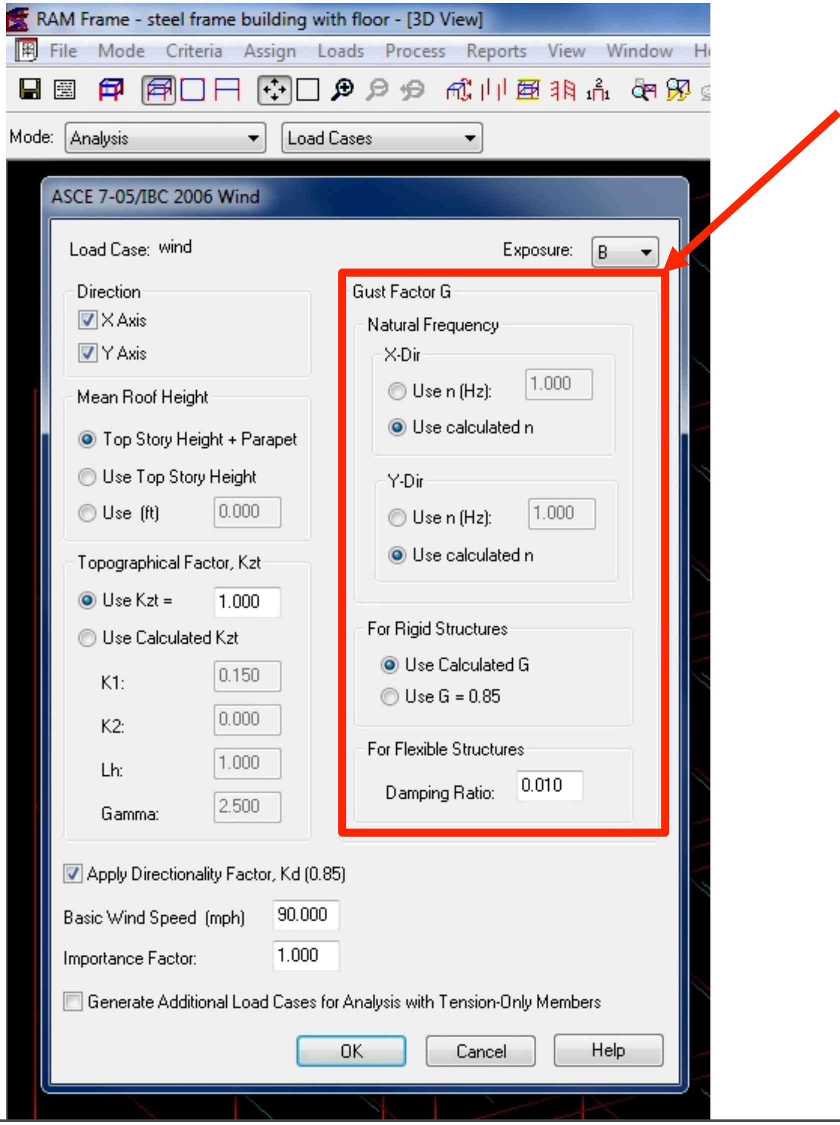
implementation using commercial building software

- most software programs:
  - don't give you the tools for calculating Gust factors
    - in many cases, I think this is a good thing
    - one of the software developers even go so far as to say "We have deliberately not **<u>automated</u>** the whole process because we don't think it is rational or even possible…"
  - even less give you an automated process for performing a full dynamic analysis for wind
  - the following examples are to indicate where a buildings dynamic properties are used for wind design

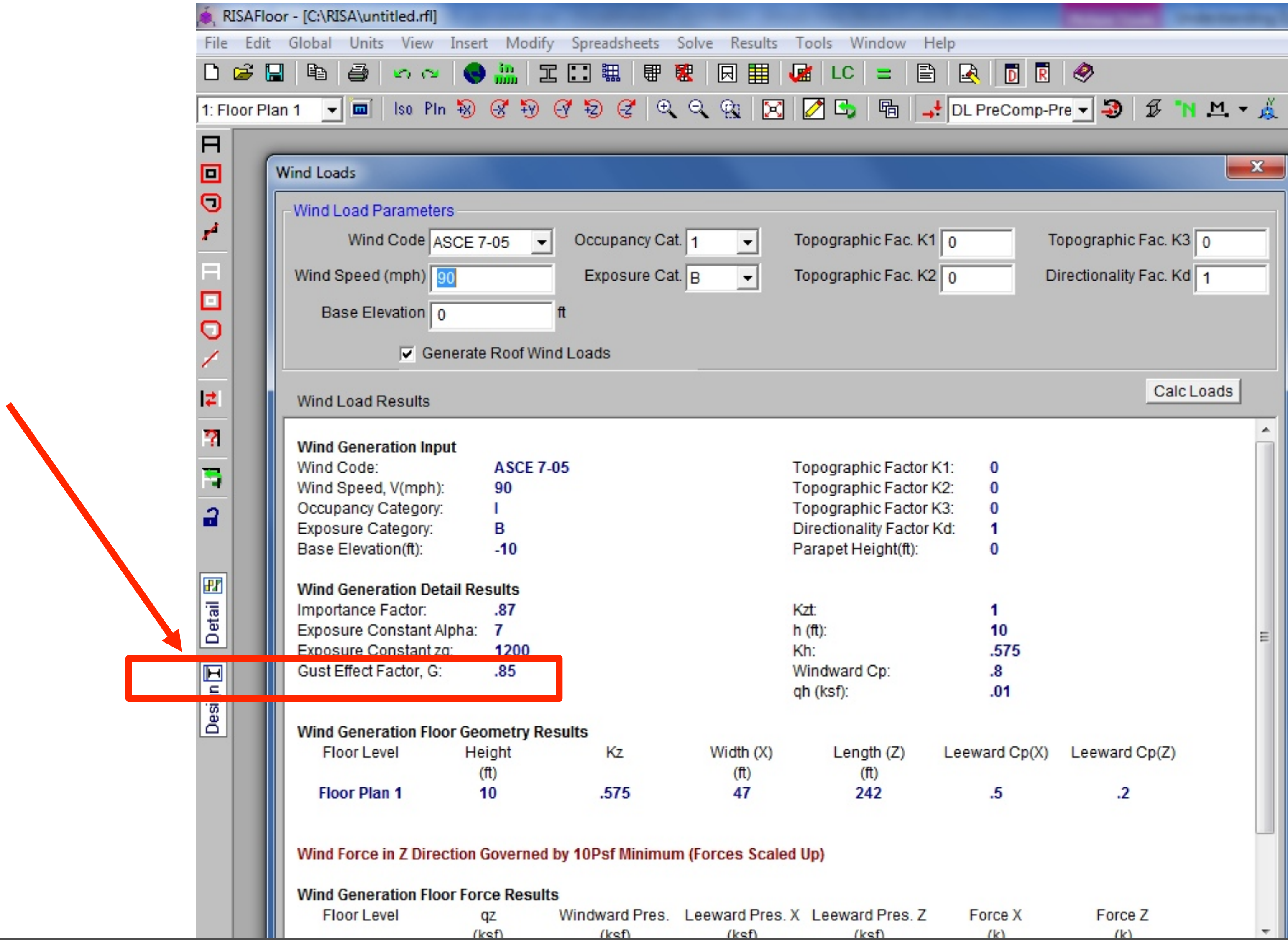
implementation using commercial building software



implementation using commercial building software



implementation using commercial building software



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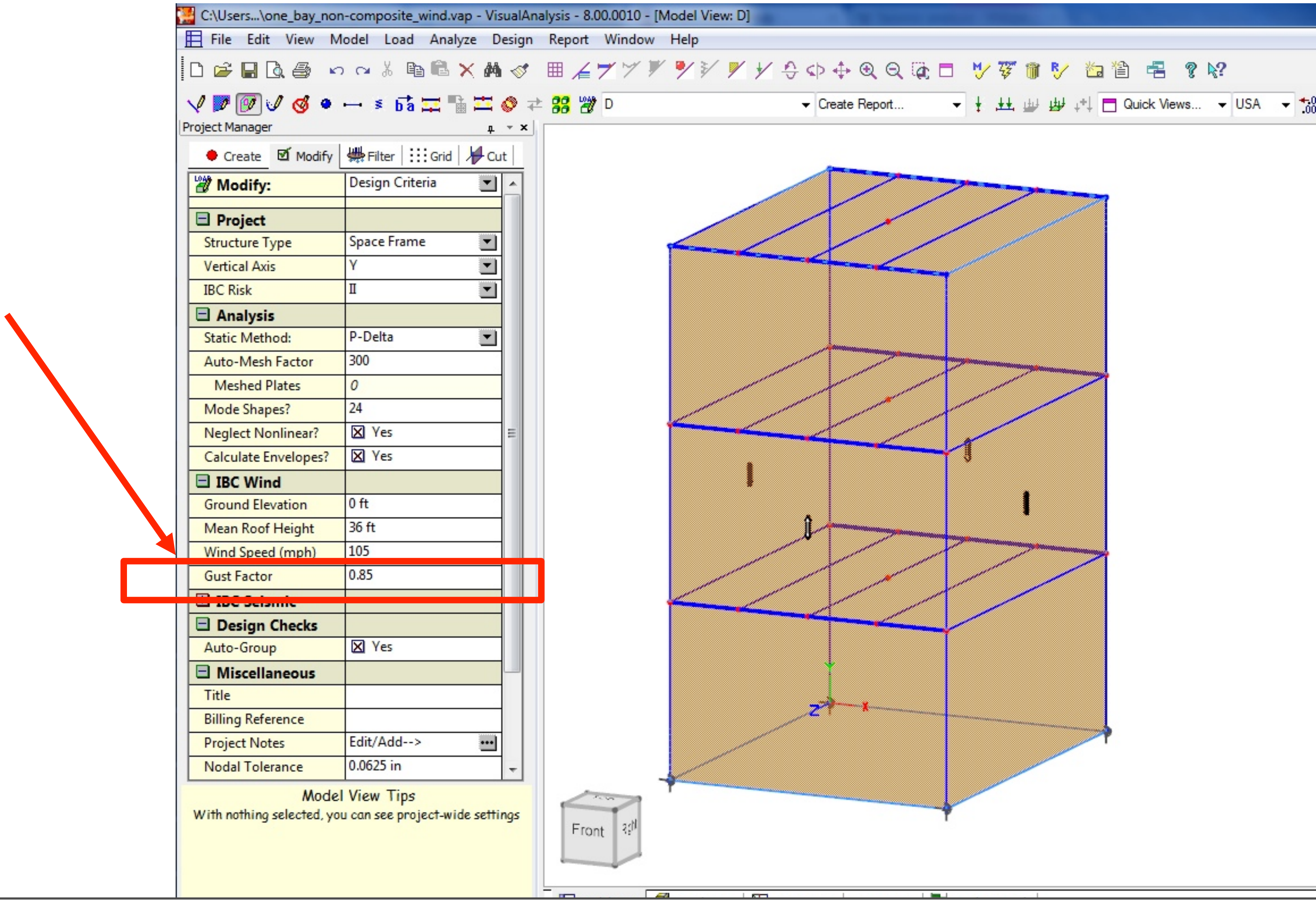

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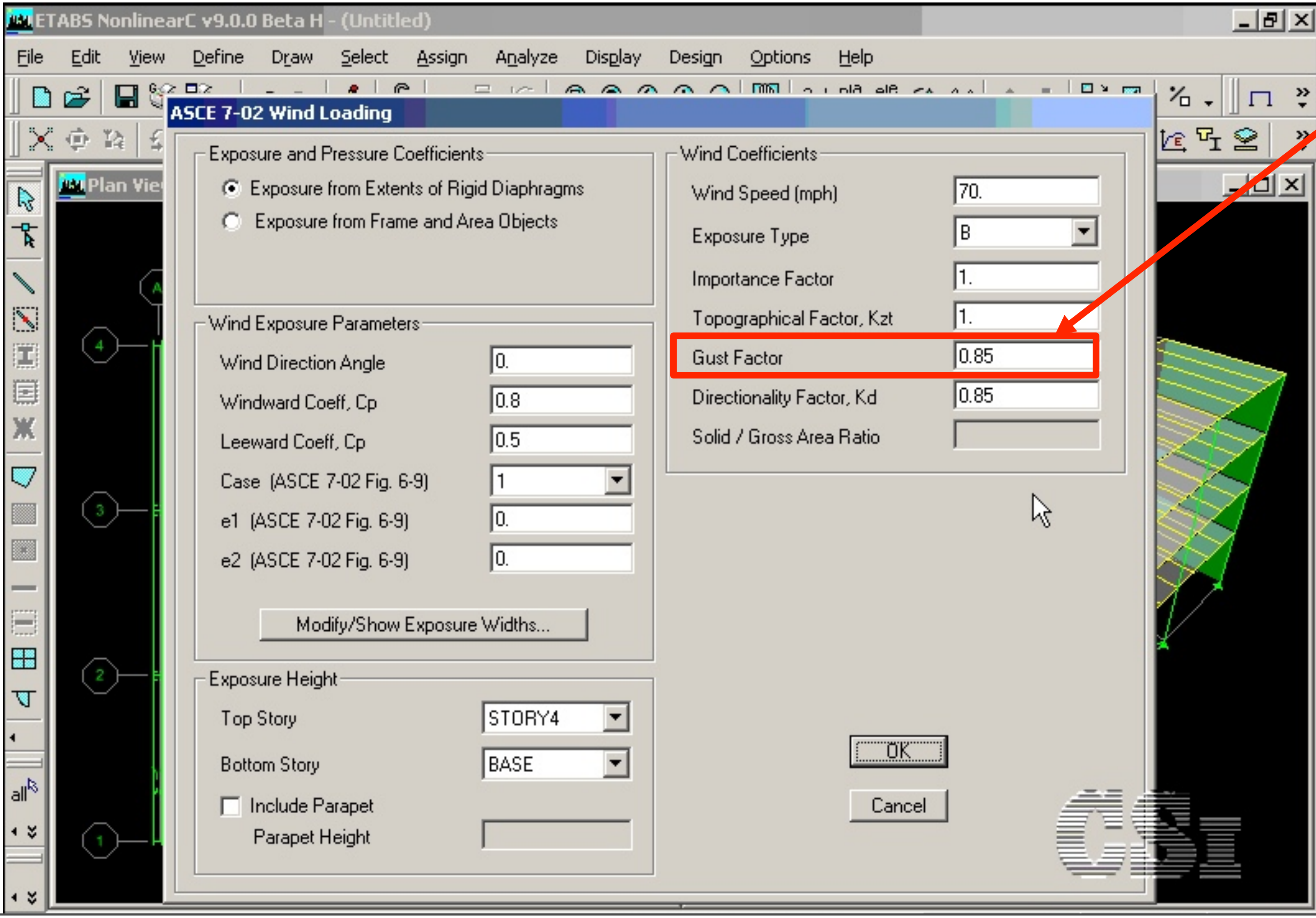


Dynamic Analysis

LOW/MODERATE SEISMIC LOADS AND BUILDING VIBRATION

seismic period determination

- ASCE 7-10 allows a "properly substantiated analysis" to determine the fundamental building period
- most commercial building software programs will quickly and easily perform an eigenvalue analysis to determine the mode shapes and periods of a building
- it is important to note that the periods determined using an eigenvalue analysis can be significantly longer than those determined using the approximate equations primarily due to three factors:
  - analytical model on which the eigenvalue analysis is performed does not generally include the stiffening effect of the non-structural infill and cladding that is present in the actual building
  - analytical model does not generally include the stiffening effect of "gravity-only" columns, beams, and slabs

Ref. William P. Jacobs, V, P.E.: STRUCTURE Magazine (June 2008); Building Periods: Moving Forward (and Backward)

seismic period determination

- ASCE 7-10 limits the maximum building period for design loads
  - approximate building period, Ta, multiplied by the factor Cu from   Table 12.8-1.
  - coincides with the upper bound of building periods as determined in the same study used to determine the lower bound approximate equations
  - cap is intended to prevent possible errors resulting from erroneous assumptions
    - which could result in **un-conservative** building periods when compared to those determined under actual seismic events.
- For the determination of seismic drift, ASCE 7-10 removes the cap
  - use the building period resulting from analysis without restriction.

Ref. William P. Jacobs, V, P.E.: STRUCTURE Magazine (June 2008); Building Periods: Moving Forward (and Backward)

use approximate methods for

- empirical formulas for the calculation of the approximate building period, Ta, from section 12.8.2.1 of ASCE 7-10
  - using the approximate period, Ta, without further calculation may result in significantly overly conservative results
- these equations are based on data from several instrumented buildings subjected to ground motion during seismic events such as the San Fernando and Northridge earthquakes
- data was used to determine both lower bound and upper bound approximate period equations using regression analysis
- the formulas provided in ASCE 7-10 represent the lower bound equations and are intentionally formulated to provide a conservative (short) estimation of the

Ref. William P. Jacobs, V, P.E.: STRUCTURE Magazine (June 2008); Building Periods: Moving Forward (and Backward)

seismic design codes

- designing a building to respond elastically to seismic load would result in very high design loads
- several things engineers and "the code" do to deal with large forces from a earthquake
  - isolate structure from the ground (base isolation)
  - increase damping (passive energy dissipation)
  - allow an inelastic response
- building codes have historically assumed an inelastic response will take place
- this means that the structure will (most likely) be severely damaged during large ground motion events (maybe even moderate events)
- controlling this damage is the important goal

Ref. Professor Christopher M. Foley, Ph.D: Marquette University; class notes from "Structural Engineering for Natural Hazards Mitigation"

stiffness of a system

- is almost always non-linear in a real response to dynamic loading
- nonlinearity is implicitly handled by codes
- explicit modeling of non-linear effects is possible

Ref. Professor Christopher M. Foley, Ph.D: Marquette University; class notes from “Structural Engineering for Natural Hazards Mitigation”

reduced loading from true

- considering inelastic response
  - building can be designed for the lower force
    - but it needs to be able to sustain numerous cycles of inelastic deformation
    - an appropriate inelastic response will result in an insignificant loss of strength
      - requires adequate detailing, etc
    - as a result of the large inelastic deformations, there will be considerable structural and non-structural damage

Ref. Professor Christopher M. Foley, Ph.D: Marquette University; class notes from “Structural Engineering for Natural Hazards Mitigation”

ASCE 7 seismic design

- design response spectrum creates a cookbook methodology to determine "equivalent" static design loads required from dynamic load
- allows engineers to focus on:
  - mass
  - stiffness
- determine building period → building loads

Ref. Professor Christopher M. Foley, Ph.D: Marquette University; class notes from "Structural Engineering for Natural Hazards Mitigation"

ASCE 7 seismic design

- to account for different systems and their dynamic properties the code uses a Response Modification Factor, R, accounts for:
  - damping
  - ductility (roughly a ratio of inelastic/elastic response)
  - anticipated structure strength
  - past performance
  - inherent redundancy

Ref. Professor Christopher M. Foley, Ph.D: Marquette University; class notes from "Structural Engineering for Natural Hazards Mitigation"

ASCE 7 seismic design

- seismic loads are high frequency, low period events
  - resonance occurs with systems that have high frequency, low periods
    - so systems with relatively lower frequencies, and higher periods are preferable
    - significant, but not the only important factor
  - also, ductility allows us to reasonably reduce design loads and allow the structure to experience inelastic behavior
    - high R values are a must in high seismic zones, in fact code prohibits low R systems in higher seismic design categories
    - more significant property in seismic design
      - less to do with dynamic properties (natural period)
      - more to do with physical properties of material and ability to

Ref. Professor Christopher M. Foley, Ph.D: Marquette University; class notes from "Structural Engineering for Natural Hazards Mitigation"

ASCE 7 seismic design

Equivalent Lateral Force Analysis

- need approximate period (if allowed) or…
- fundamental period from properly substantiated analysis
- allowed in low, moderate seismic areas, SDC B and C
- limited in SDC D, E, and F according to ASCE 7-10 Table 12.6-1
  - not allowed in buildings with irregularities because the procedure is based on the assumption of gradually varying stiffness and mass along the height, and negligible torsional response

ASCE 7 seismic design

Modal Response Spectrum Analysis

- full dynamic analysis
- need 90% mass participation from modes
- various modes combined by SRSS, CQC, or CQC-4
    - for 3D models, use CQC or CQC-4
- scaling of forces required when:
    - initially, values divided by R/I_e (to account for damping, inelasticity, etc)
        - individual member forces, support forces
    - however, response from modal based shear when less than 85% of base shear from the equivalent lateral force procedure
        - forces shall be multiplied by $0.85 * V_{ELF} / V_{RSA}$
- allowed in all seismic design categories

ASCE 7 seismic design

Equivalent Static Analysis

- This approach defines a series of forces acting on a building to represent the effect of earthquake ground motion, typically defined by a seismic design response spectrum. It assumes that the building responds in its fundamental mode. For this to be true, the building must be low-rise and must not twist significantly when the ground moves. The response is read from a design response spectrum, given the natural frequency of the building (either calculated or defined by the building code). The applicability of this method is extended in many building codes by applying factors to account for higher buildings with some higher modes, and for low levels of twisting. To account for effects due to "yielding" of the structure, many codes apply modification factors that reduce the design forces (e.g. force reduction factors).

Response Spectrum Analysis

- This approach permits the multiple modes of response of a building to be taken into account (in the frequency domain). This is required in many building codes for all except for very simple or very complex structures. The response of a structure can be defined as a combination of many special shapes (modes) that in a vibrating string correspond to the "harmonics". Computer analysis can be used to determine these modes for a structure. For each mode, a response is read from the design spectrum, based on the modal frequency and the modal mass, and they are then combined to provide an estimate of the total response of the structure. Combination methods include the following:
- absolute – peak values are added together
- square root of the sum of the squares (SRSS)
- complete quadratic combination (CQC) – a method that is an improvement on SRSS for closely spaced modes
- The result of a response spectrum analysis using the response spectrum from a ground motion is typically different from that which would be calculated directly from a linear dynamic analysis using that ground motion directly, since phase information is lost in the process of generating the response spectrum.

ASCE 7 seismic design

Other procedures more common in high seismic zones

- Linear Dynamic Analysis
- Non-linear Static Analysis (Pushover)
- Non-linear Dynamic Analysis

ASCE 7 seismic design

Linear Dynamic Analysis

- tall buildings, buildings with torsional irregularities, or non-orthogonal systems, a dynamic procedure is required. In the linear dynamic procedure, the building is modeled as a multi-degree-of-freedom (MDOF) system with a linear elastic stiffness matrix and an equivalent viscous damping matrix.
- The seismic input is modeled using either modal spectral analysis or time history analysis but in both cases, the corresponding internal forces and displacements are determined using linear elastic analysis. The advantage of these linear dynamic procedures with respect to linear static procedures is that higher modes can be considered. However, they are based on linear elastic response and hence the applicability decreases with increasing nonlinear behavior, which is approximated by global force reduction factors.
- In linear dynamic analysis, the response of the structure to ground motion is calculated in the time domain, and all phase information is therefore maintained. Only linear properties are assumed. The analytical method can use modal decomposition as a means of reducing the degrees of freedom in the analysis.

Non-linear Static Analysis (Pushover)

- In general, linear procedures are applicable when the structure is expected to remain nearly elastic for the level of ground motion or when the design results in nearly uniform distribution of nonlinear response throughout the structure. As the performance objective of the structure implies greater inelastic demands, the uncertainty with linear procedures increases to a point that requires a high level of conservatism in demand assumptions and acceptability criteria to avoid unintended performance. Therefore, procedures incorporating inelastic analysis can reduce the uncertainty and conservatism.
- A pattern of forces is applied to a structural model that includes non-linear properties (such as steel yield), and the total force is plotted against a reference displacement to define a capacity curve. This can then be combined with a demand curve (typically in the form of an acceleration-displacement response spectrum (ADRS)). This essentially reduces the problem to a single degree of freedom system.
- Nonlinear static procedures use equivalent SDOF structural models and represent seismic ground motion with response spectra. Story drifts and component actions are related subsequently to the global demand parameter by the pushover or capacity curves that are the basis of the non-linear static procedures.

Non-linear Dynamic Analysis

- Nonlinear dynamic analysis utilizes the combination of ground motion records with a detailed structural model, therefore is capable of producing results with relatively low uncertainty. In nonlinear dynamic analyses, the detailed structural model subjected to a ground-motion record produces estimates of component deformations for each degree of freedom in the model and the modal responses are combined using schemes such as the square-root-sum-of-squares.
- In non-linear dynamic analysis, the non-linear properties of the structure are considered as part of a time

DYNAMIC ANALYSIS

USING COMMERCIAL SOFTWARE FOR LOW/MODERATE SEISMIC AREAS

implementation using commercial building software

- how mass is used in dynamic models
  - how to calculate
    - some programs store mass separate from building loads
    - some use one load case or combination as mass
  - members and plates
    - masses get lumped at nodes
    - split elements and plates to more evenly distribute
  - floors
    - mass gets lumped at a single location per floor for a rigid diaphragm
      - limits dof (simplifies the model)
  - additional applied mass on member or nodes
    - good idea for perimeter wall that is not supported
  - dynamic analysis is sensitive to the discretization of you model (how many members, nodes, dof)
    - remember FEA results are approximate

implementation using

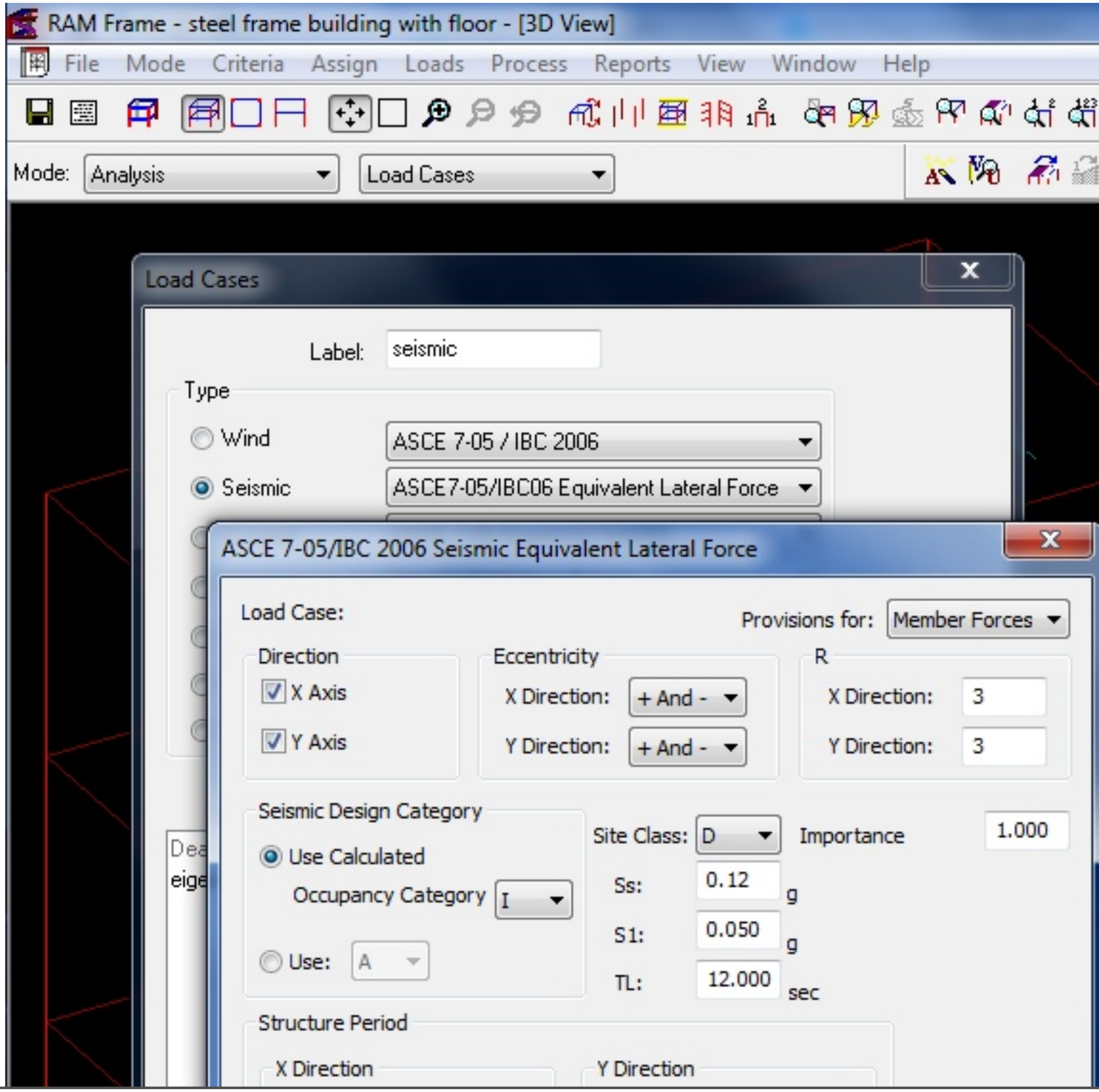
- first and foremost
  - get the TRUE mass modeled
    - not always the same as dead load
      - many times we are conservative with dead loads (+)
      - remember, more mass (+) leads to longer periods and less seismic load
    - remember sustained live load (code requires this for storage) and 20% of snow when greater than 30psf
  - get the TRUE stiffness modeled
    - ignoring partial fixity in joints (beam ends, column splices, column base plates, etc. etc.) for example may lead to conservative positive moments for beam design, but also reduces stiffness and leads to less seismic load
  - for modal analysis, do your best to consider the most likely damping percentages (remember elastic vs

implementation using commercial building software

implementation using commercial building software

implementation using commercial building software

implementation using commercial building software



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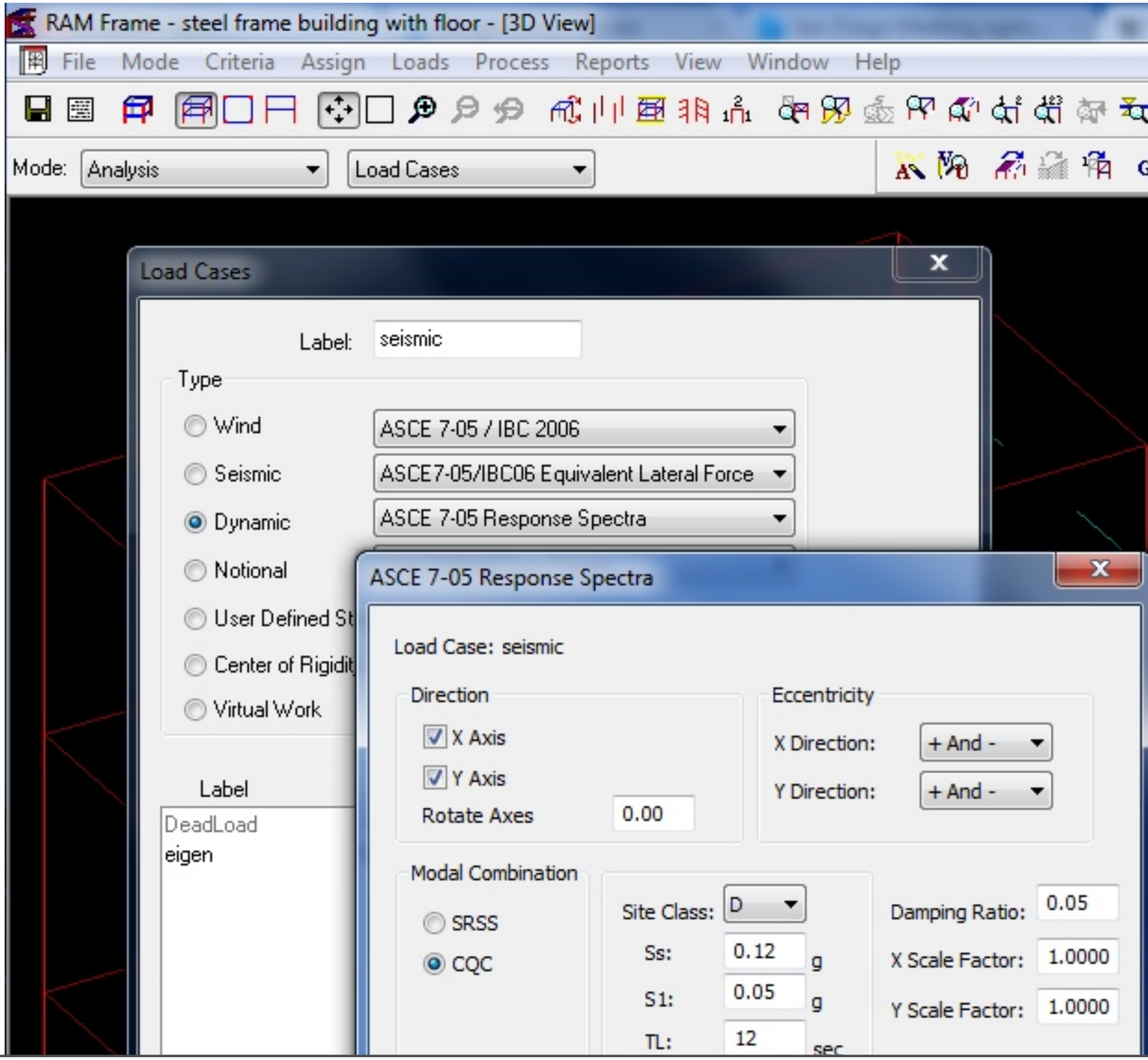

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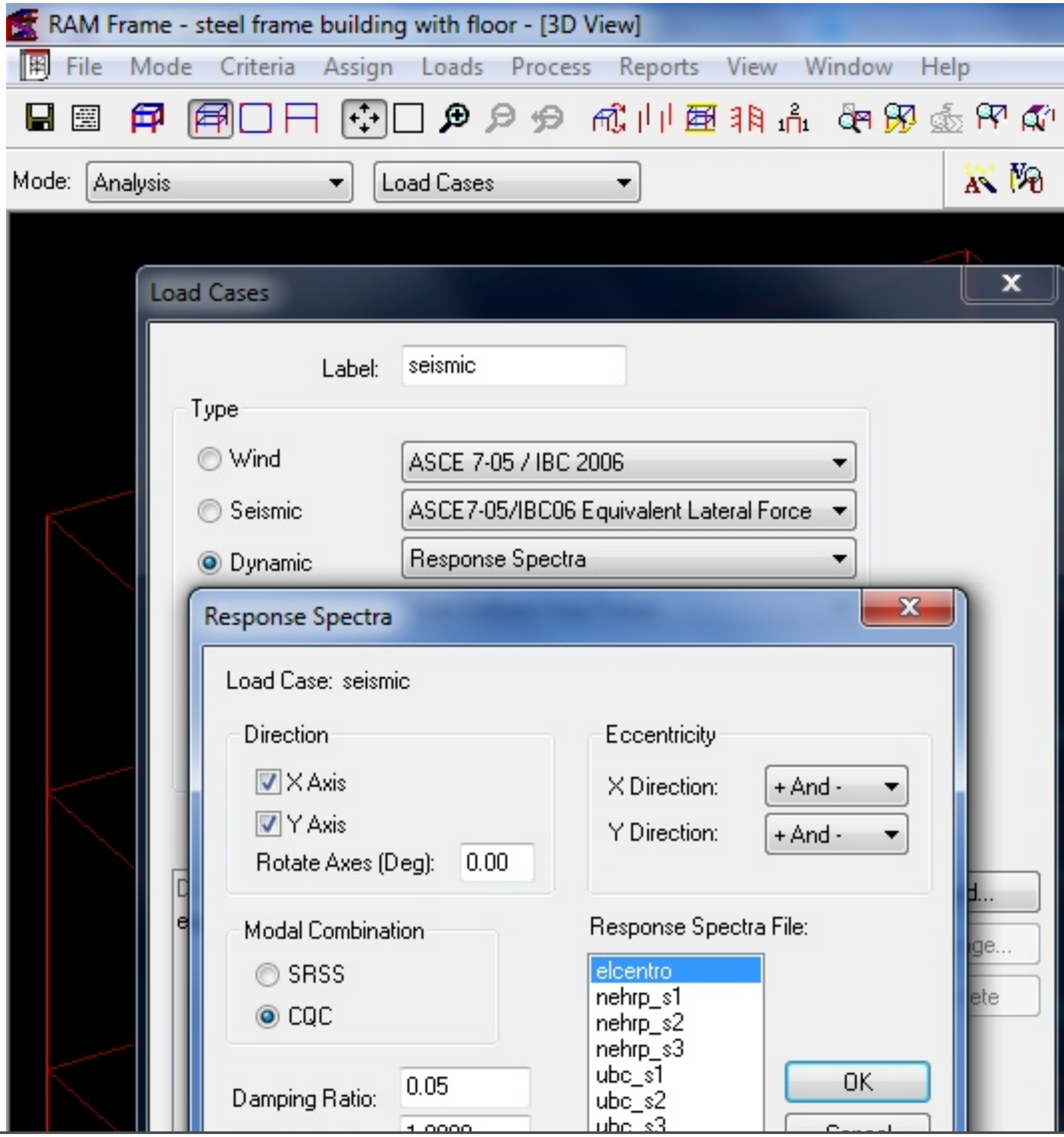

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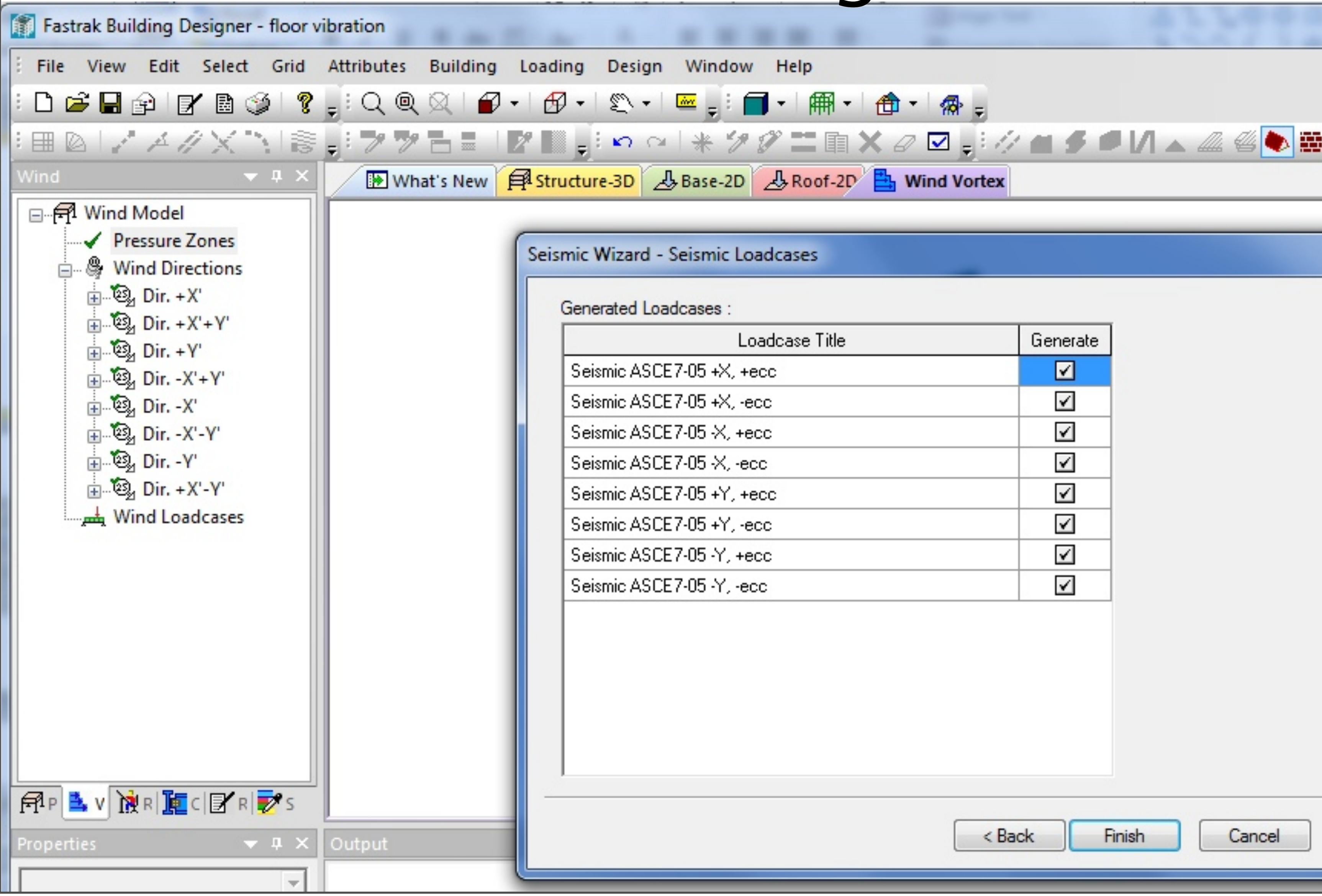

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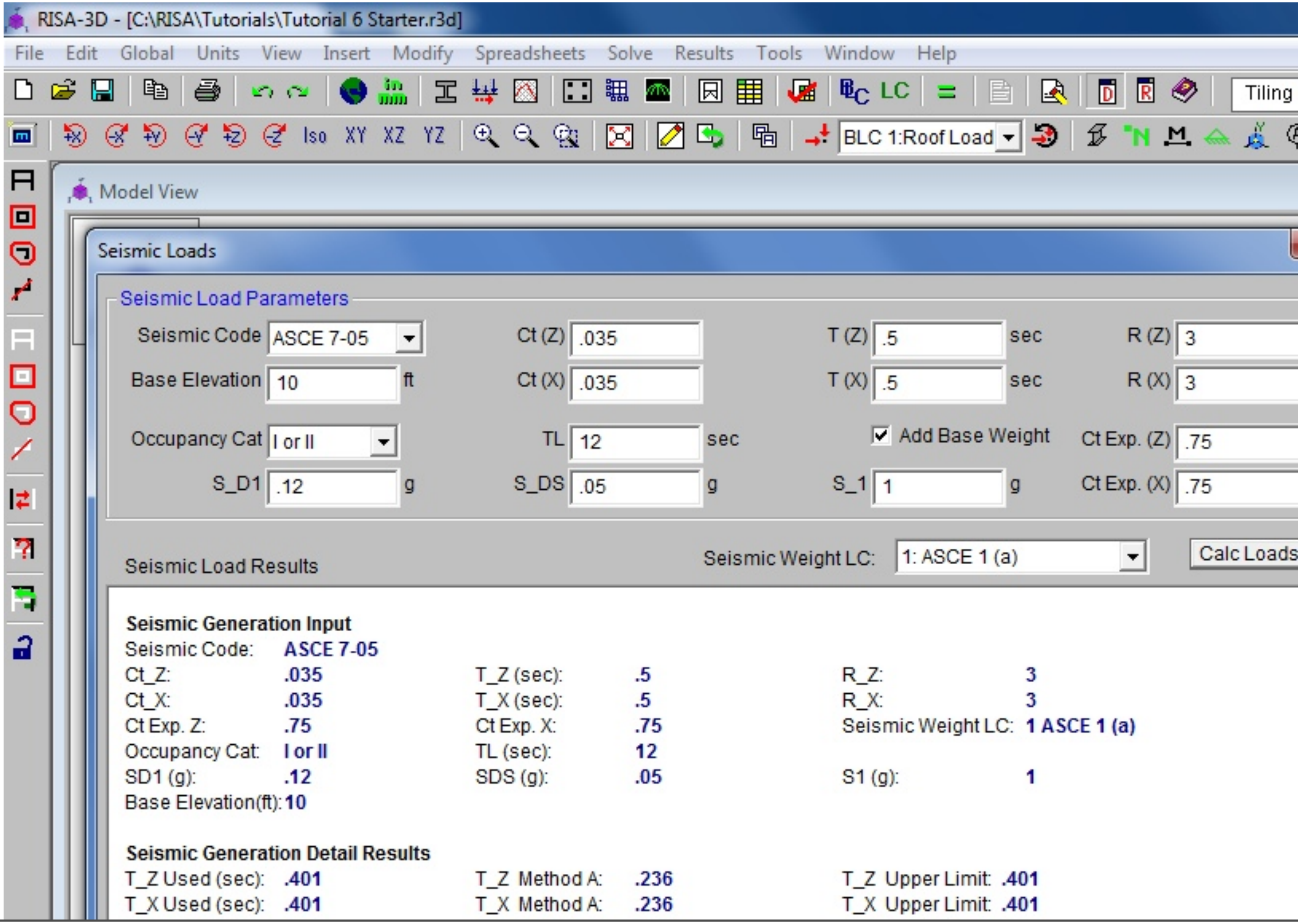

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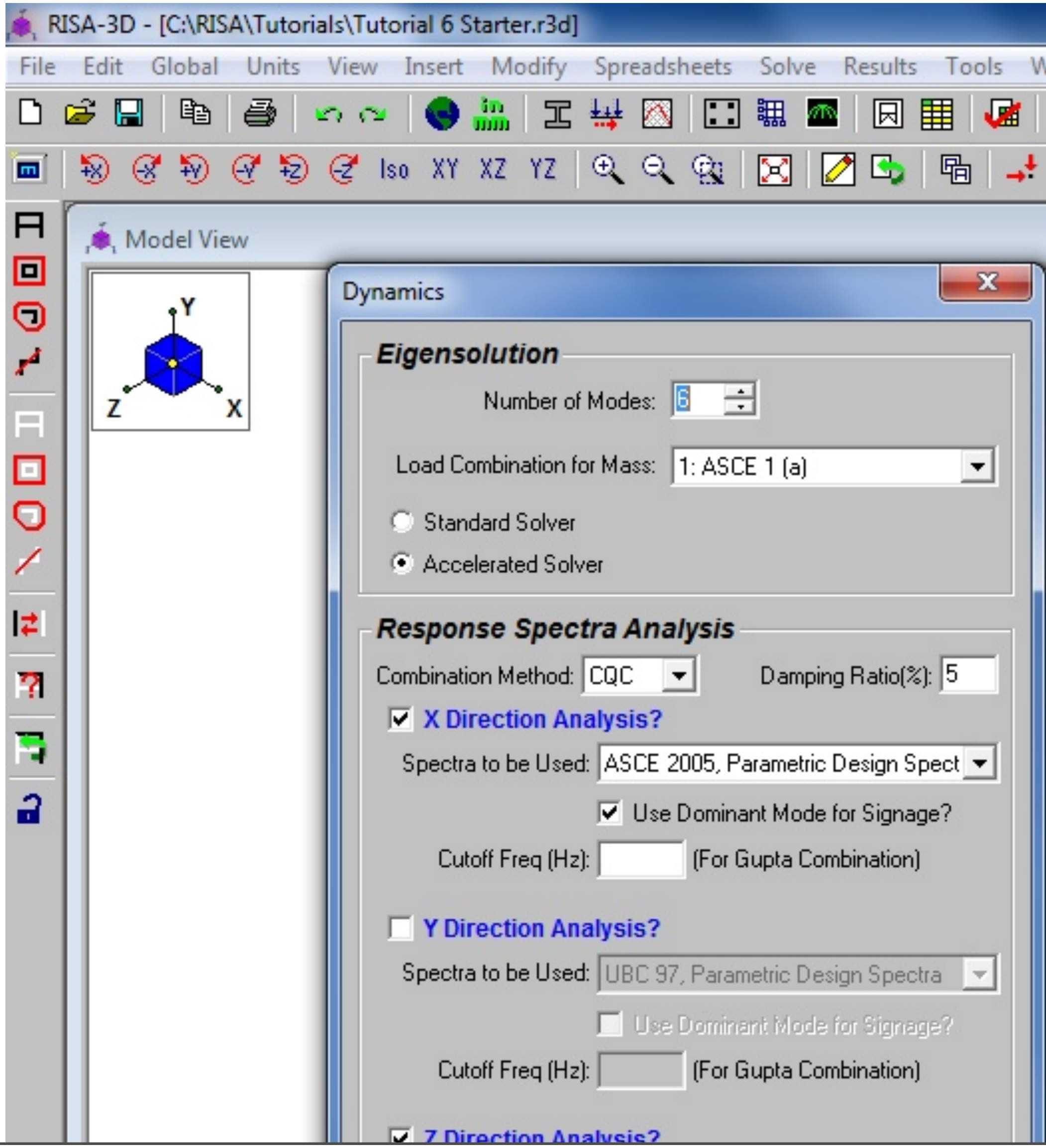

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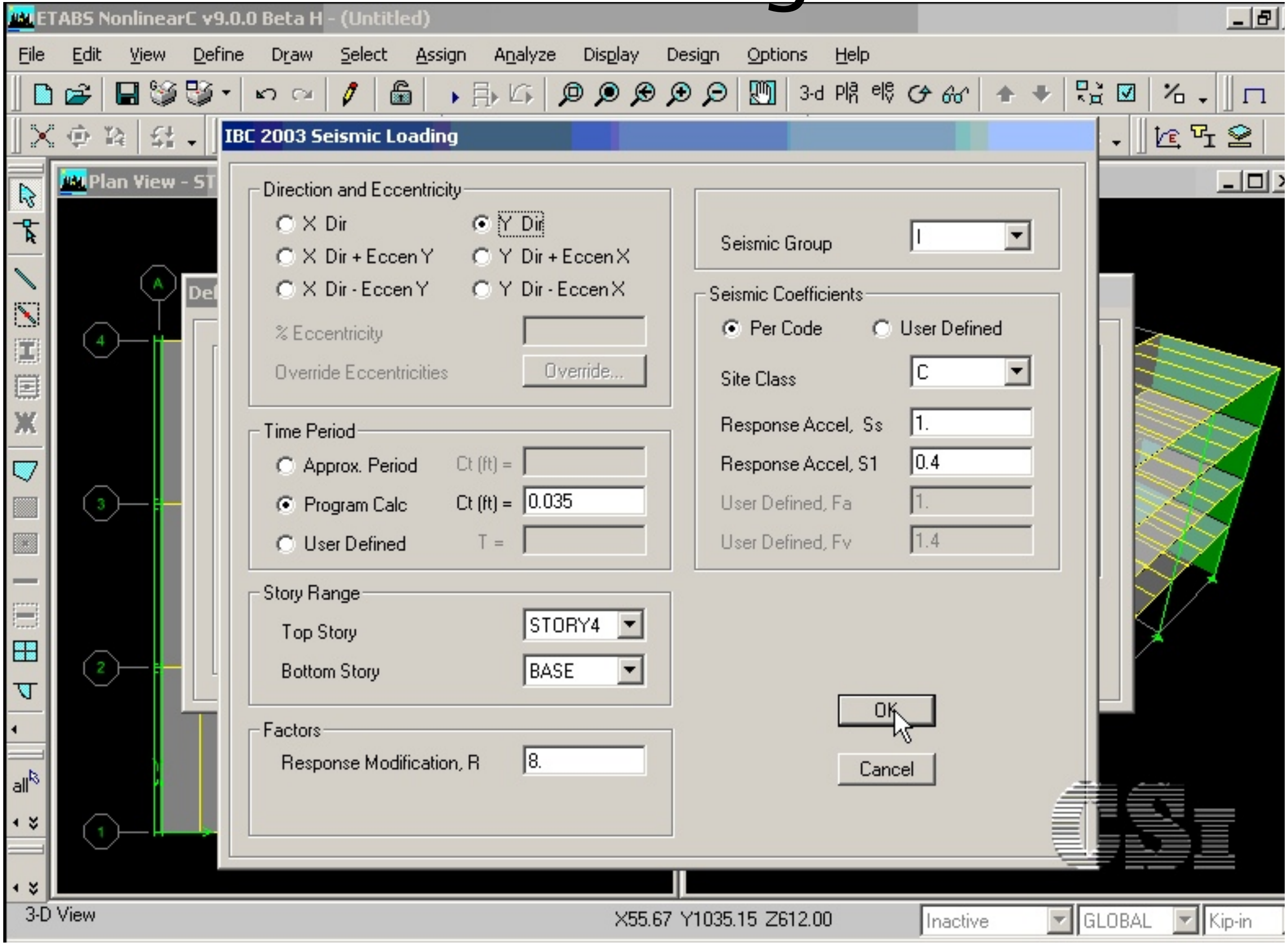

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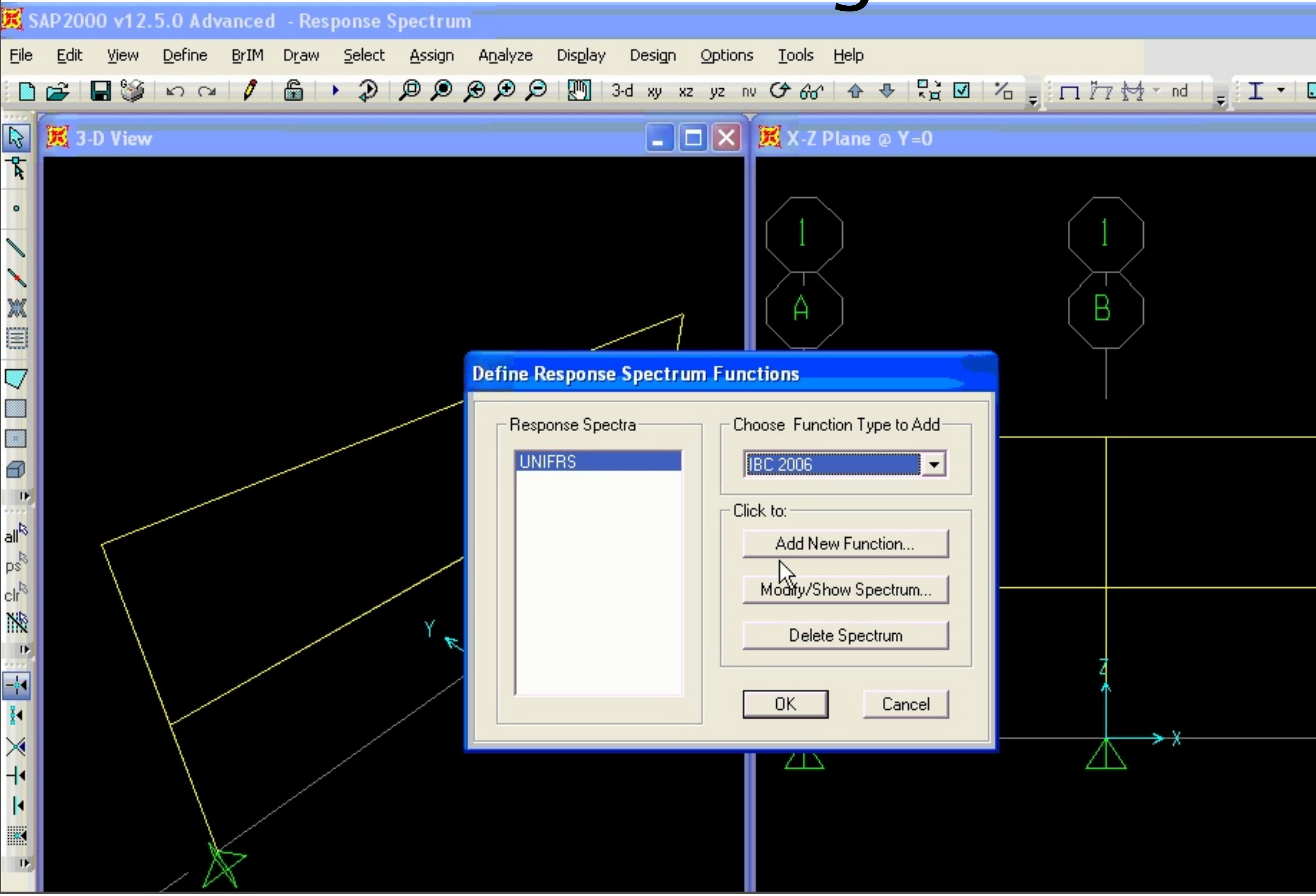

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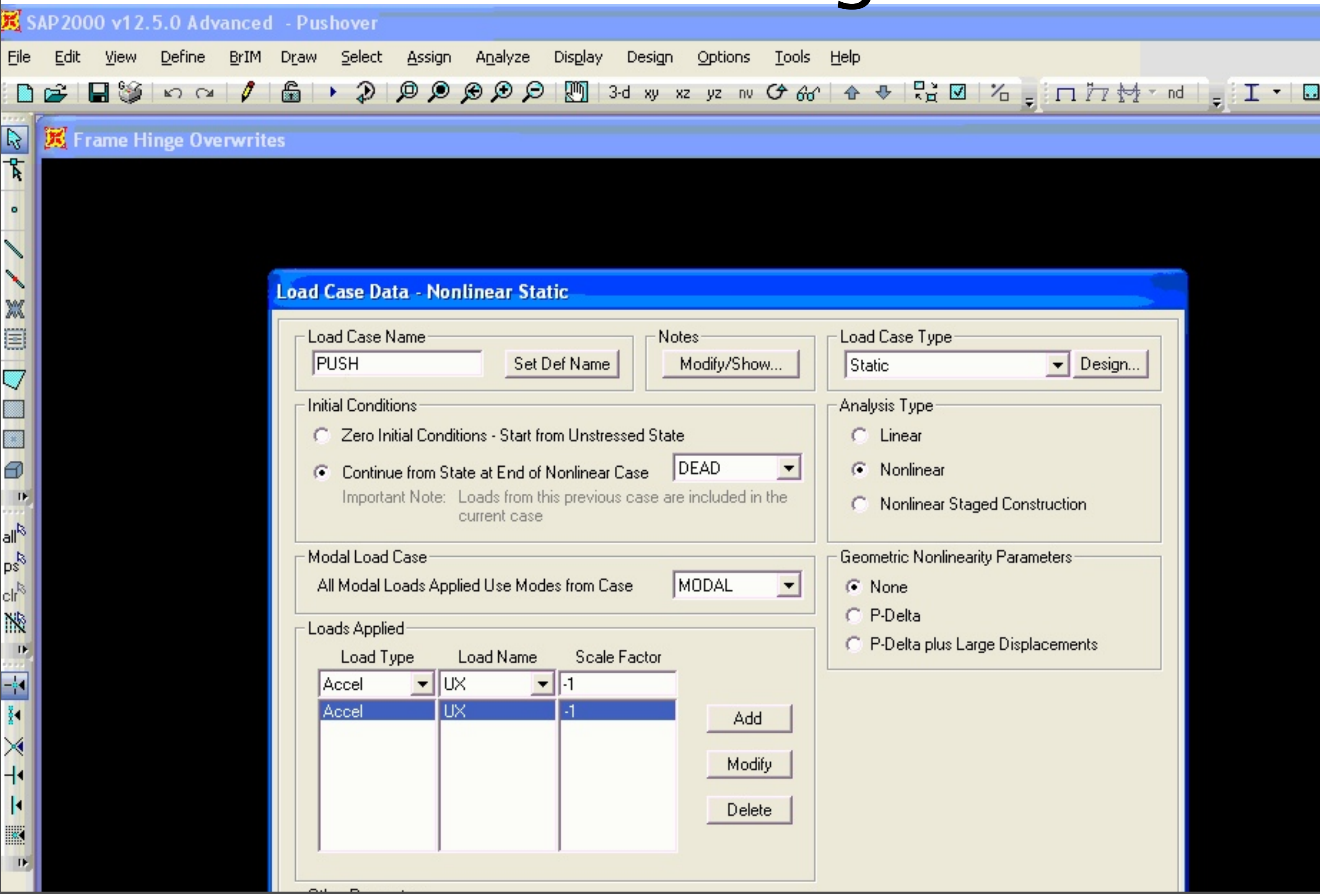

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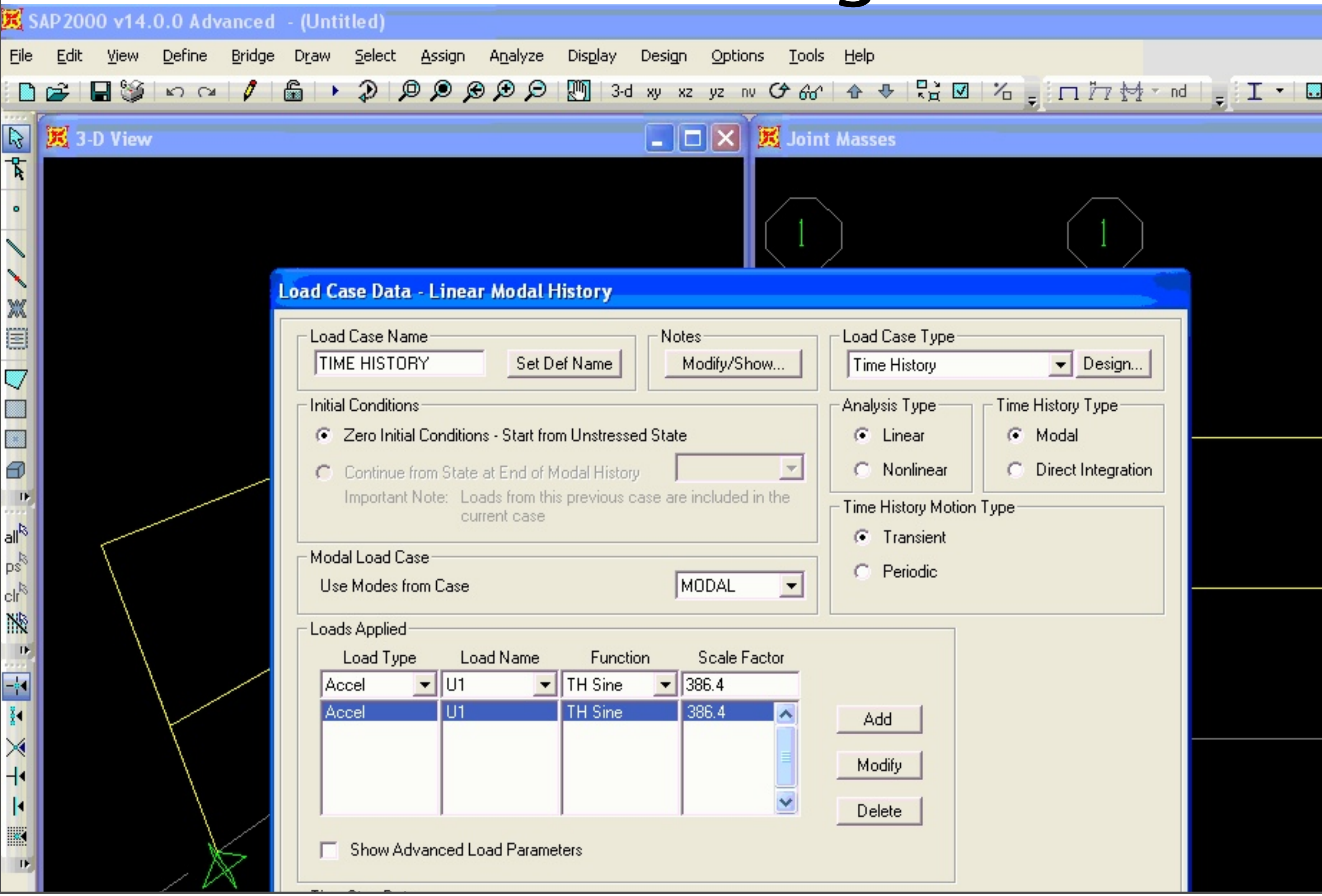


implementation using commercial building software

Dynamic Analysis

AVOIDING POTENTIAL PROBLEMS

dynamics modeling tips

- some compromise must be made in you finite element model
  - in general, the mass in your model will be lumped at nodes (automatically in some progams)
  - shear buildings, where the mass is considered lumped at the stories are much easier to successfully model than other structures
- distributed mass. It is often helpful to define a load combination just for your dynamic mass case, separate from your “Dead Load” static
  - dynamic mass load combination will often be modeled very differently
- If you apply your dynamic mass with distributed loads or surface loads on members/plates that are adjacent to supports, remember that the some of the load will go directly into the support and be lost to the dynamic solution.
  - the mass that can actually vibrate freely is your “active mass”, as opposed to your “static mass” which includes the mass lost into the supports.
  - if you are having trouble getting 90% mass participation, you should roughly calculate the amount of mass that is being lost into your supports. You may need to reapply some of your mass as joint loads to your free joints.
  - or you may want to add more free joints to your model, by splitting up your plates or beams.
- You want to lump the mass at fewer points to help the solution converge faster, however you have to be careful to still capture the essence of the dynamic behavior of the structure.

don’t forget about accidental torsion in dynamic analysis

- ASCE 7-10 requires the consideration of accidental torsional moments caused by "an assumed displacement of the center of mass each way from its actual location by a distance equal to 5% of the dimension of the building perpendicular to the direction of the applied forces"
  - required to be considered in both the equivalent static load procedure and dynamic analysis.
- code requirements for evaluating accidental torsion in the equivalent lateral force procedure are implemented in most building analysis tools in a straightforward manner.
  - some building analysis software users are not clear on how to model accidental torsion in dynamic analysis.
- however, amplification of accidental torsion is <u>not</u>

Ref. Professor Sam Kassegne, Ph.D: Professor of mechanical engineering at San Diego State University; “Basics of Dynamic Analysis”

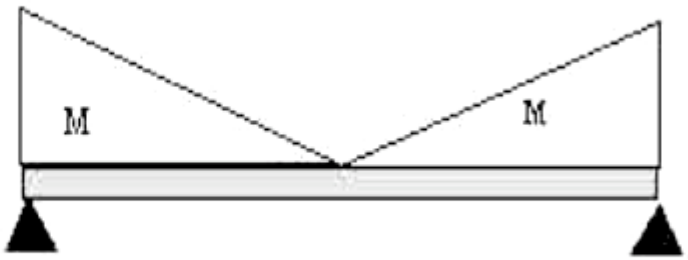
don’t forget about orthogonal effects in dynamic analysis

- well designed buildings are expected to resist earthquake loads in all possible directions
- structures with a horizontal irregularity and SDC C, or structures with columns partaking in load resistance in both directions and exceeding 20% design capacity
  - 100% of the earthquake load in a given direction
  - plus 30% (or 40% depending on the code) of an earthquake load in the perpendicular direction.
- Some commercial programs do not handle this requirement automatically
  - In such cases, users need to run two orthogonal dynamic load cases and manually combine them as per the code specification

Ref. Professor Sam Kassegne, Ph.D: Professor of mechanical engineering at San Diego State University; “Basics of Dynamic Analysis”

how to use dynamic analysis results in design load combinations

- Analysis results related to a dynamic load are obtained after modal contributions from each dynamic mode are combined
  - CQC
  - SRSS
  - all resu n, such as for momen



- In some cases, the sign of analysis results is required
- that analysis results for a dynamic load case are adjusted with a sign.
  - some programs consider 8 load cases that would consider +M, -M, +V, -V, +A, -A forces to capture the worst case

Ref. Professor Sam Kassegne, Ph.D: Professor of mechanical engineering at San Diego State University; "Basics of Dynamic Analysis"

models that don’t work well

- multiple separate frames
  - be careful of semi-isolated areas
    - hard to get required mass participation.
- models that have lateral support above the base
- models that are properly discretized (too course of a mesh)
- too few dof - not a true representation, overly simplified (rigid diaphragms for models that aren’t close enough to being truly rigid)
- too many dof - too complex of a model, hard to get mass participation with reasonable amount of modes

avoiding problems with

- For dynamic analysis of 3D structures, use CQC only.
  - The code suggests you use CQC or CQC-4
  - SRSS has been observed to give erroneous results for unsymmetrical three-dimensional buildings
- Look closely at:
  - deflected shape
  - mode-shapes
  - building story shear output for each analysis run
- Any undesirable behavior could easily be detected by these outputs
- Also investigate if boundary conditions such as foundation nodes have been properly applied on the model.

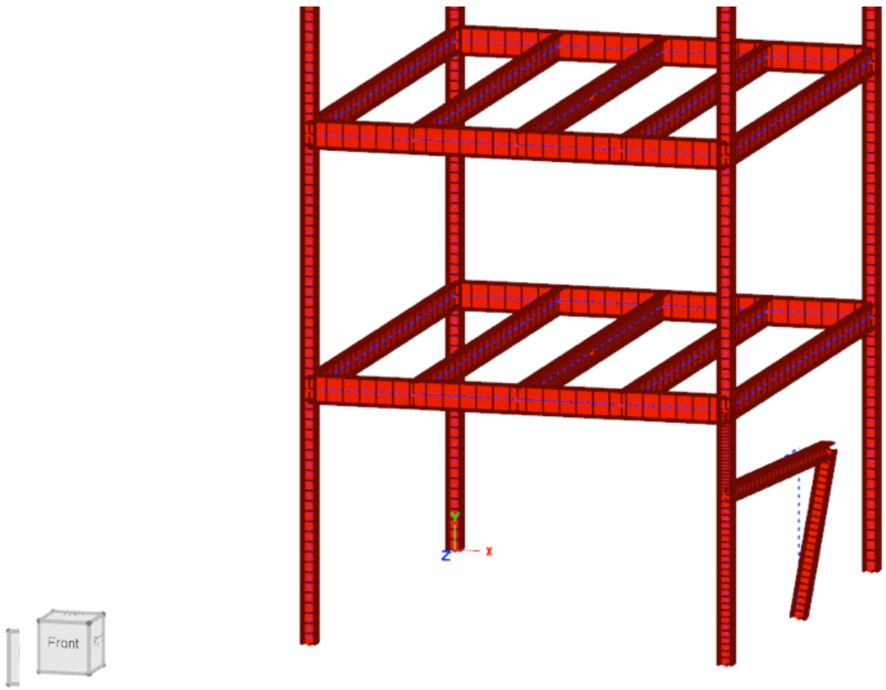
- Only when you are satisfied with the general behavior

avoiding problems with

- modes where only a small part of the model is vibrating and the rest of the model is not
- may not be obvious from looking at the numeric mode shape results
  - can usually be spotted by animating the mode shape
- make it difficult to get enough mass participation in the response spectra analysis
  - local modes don't usually have much mass associated with them
  - solving for a substantial number of modes but getting very little or no mass participation would indicate that the modes being found are localized modes
- sometimes, localized modes are due to modeling errors (erroneous boundary conditions, members not attached to plates correctly, etc.).

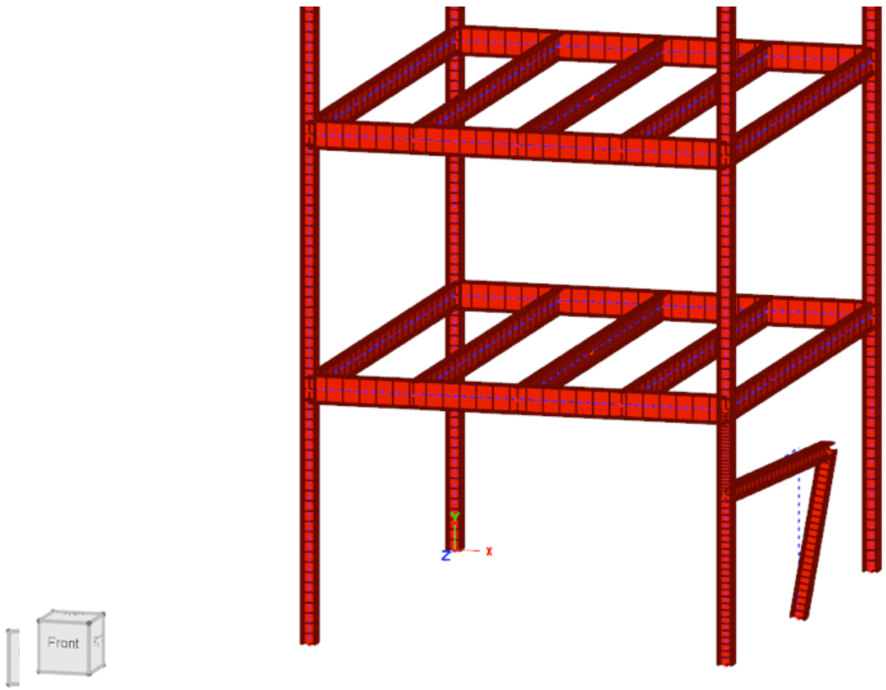
avoiding problems with

avoiding problems with



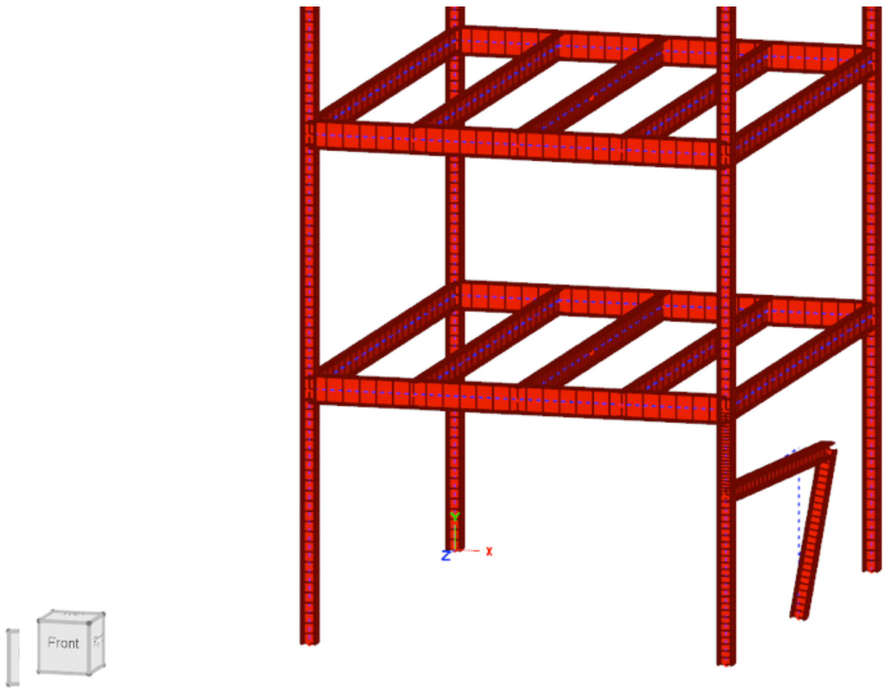
front view

avoiding problems with



isometric view

avoiding problems with



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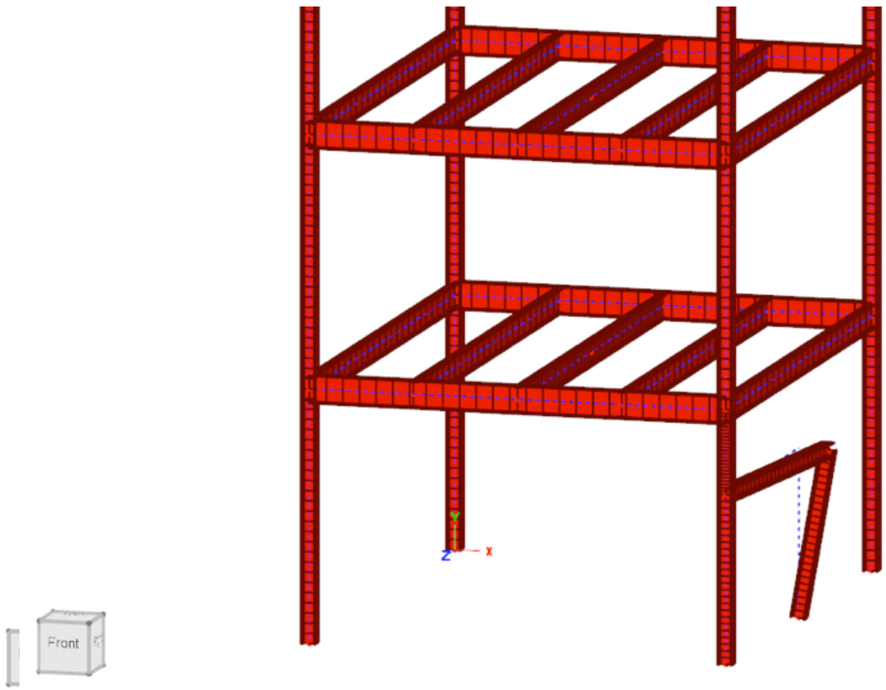

isometric view

avoiding problems with dynamic analysis – localized modes

Mode Shape Results									
Result Case Name	f(Hz)	T(sec)	X Part	Y Part	Z Part	X Mass	Y Mass	Z Mass	Total Mas
						K	K	K	K
Mode # 1 (0.36 Hz)	0.36	2.779	0.006	0	0	1.558	0	0.015	243.544
Mode # 2 (0.558 Hz)	0.558	1.792	0	0	0.816	0	0	198.632	243.544
Mode # 3 (0.846 Hz)	0.846	1.182	0.809	0	0	196.957	0	0	243.544
Mode # 4 (0.899 Hz)	0.899	1.113	0	0	0.001	0	0	0.201	243.544
Mode # 5 (1.12 Hz)	1.12	0.893	0	0	0.086	0	0	20.889	243.544
Mode # 6 (1.23 Hz)	1.229	0.814	0	0	0.005	0	0	1.171	243.544
Mode # 7 (1.25 Hz)	1.249	0.801	0	0	0.023	0	0	5.549	243.544
Mode # 8 (1.28 Hz)	1.276	0.783	0.015	0	0	3.684	0	0	243.544
Mode # 9 (1.29 Hz)	1.288	0.777	0.003	0	0	0.659	0	0	243.544
Mode #10 (1.41 Hz)	1.408	0.71	0.034	0	0	8.393	0	0	243.544
Mode #11 (2.14 Hz)	2.136	0.468	0	0	0.008	0	0	1.908	243.544
Mode #12 (2.42 Hz)	2.419	0.413	0	0	0.001	0	0	0.177	243.544
Mode #13 (2.91 Hz)	2.914	0.343	0.048	0	0	11.614	0	0	243.544
Mode #14 (2.92 Hz)	2.924	0.342	0.041	0	0	10.087	0	0	243.544
Mode #15 (3.13 Hz)	3.127	0.32	0	0	0.008	0	0	2.059	243.544
Mode #16 (3.24 Hz)	3.238	0.309	0	0	0.019	0	0.001	4.664	243.544
Mode #17 (3.42 Hz)	3.415	0.293	0	0.041	0	0	9.943	0	243.544
Mode #18 (3.48 Hz)	3.479	0.287	0	0.012	0	0	2.802	0	243.544
Mode #19 (3.5 Hz)	3.5	0.286	0	0.121	0	0	29.439	0	243.544
Mode #20 (4.26 Hz)	4.264	0.235	0	0	0	0	0	0	0
Mode #21 (4.42 Hz)	4.416	0.226	0	0	0.01	0	0	2.326	243.544
Mode #22 (4.54 Hz)	4.542	0.22	0	0	0.003	0	0	0.644	243.544
Mode #23 (4.81 Hz)	4.809	0.208	0.009	0	0	2.256	0	0.003	243.544
Mode #24 (4.83 Hz)	4.832	0.207	0.013	0	0	3.189	0	0.002	243.544

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the end

QUESTIONS?

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