Lecture 5
Building Irregularities

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4.1.8.3. General Requirements

1) The *building* shall be designed to meet the requirements of this subsection and of the design standards referenced in Section 4.3.
2) Structures shall be designed with a clearly defined load path, or paths, to transfer the inertial forces generated in an earthquake to the supporting ground .
3) The structure shall have a clearly defined Seismic Force Resisting System(s) (SFRS) as defined in Article 4.1.8.2.
4) The SFRS shall be designed to resist 100% of the earthquake loads and their effects.
8) Structural modelling shall be representative of the magnitude and spatial distribution of the mass of the *building* and stiffness of all elements of the SFRS, which includes stiff elements that are not separated in accordance with Sentence 4.1.8.3.(6), and shall account for
   a) the effect of cracked sections in reinforced concrete and reinforced masonry elements
   b) the effect of the finite size of members and joints
   c) sway effects arising from the interaction of gravity loads with the displaced configuration of the structure, and
   d) other effects which influence the *buildings* lateral stiffness.

4.1.8.7. Methods of Analysis

Equivalent Static Force Procedure used

- areas of low seismicity, or
- regular, H<60m and T<2s
- not torsionally irregular, H<20m,T<0.5s

Dynamic Analysis

- default method
- base shear tied back to statically determined

STRUCTURAL IRREGULARITIES

- Static lateral force method is based on a regular distribution of stiffness and mass in structure.
- It becomes less accurate as the structure varies from this assumption.
- Historically – regular buildings perform better in earthquakes than do irregular buildings. Layouts prone to damage are:
    - torsionally eccentric ones.
    - “in” or “out” of plane offsets of the lateral system.
    - cut-off lateral load elements – particularly coming down the building.
    - those with a weak storey.

STRUCTURAL IRREGULARITIES

- Irregularities defined in code address:
  - mass and/or stiffness irregularities by requiring a dynamic analysis for “taller” buildings in “higher” seismic zones (short period buildings tend to be first mode dominated – static method not bad).
  - offsets etc… treated by requiring a dynamic analysis for “taller” buildings **and** prescribing some system limitations.
  - post disaster buildings – limit irregularities (basically in “higher” zones – only mass irregularities and non-orthogonal system allowed.
- Irregularities such as “weak” storey are problematic and are treated severely in NBCC – more than in FEMA and U.B.C. Note that “weak” storey is not a “soft” storey. The “soft” storey is dealt with in the stiffness irregularity section.

4.1.8.3. General Requirements

When:

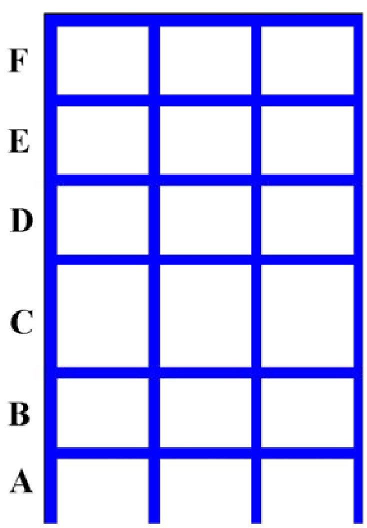
$I_E \cdot F \cdot S_{a(0.2)} > 0.35$ (i.e. – about 1/3 of Vancouver value) + any one of the 8 irregularity types.

the building is considered as *irregular.*

4.1.8.6. Structural Configuration

Type	Irregularity Type and Definition	Notes
1	**Vertical Stiffness Irregularity** Vertical stiffness irregularity shall be considered to exist when the lateral stiffness of the SFRS in a *storey* is less than 70% of the stiffness of any adjacent *storey*, or less than 80% of the average stiffness of the three *storeys* above or below.	(1) (3) (7)
2	**Weight (mass) Irregularity** Weight irregularity shall be considered to exist where the weight, W_i of any *storey* is more than 150 percent of the weight of an adjacent *storey*. A roof that is lighter than the floor below need not be considered.	(1)
3	**Vertical Geometric Irregularity** Vertical geometric irregularity shall be considered to exist where the horizontal dimension of the SFRS in any *storey* is more than 130 percent of that in an adjacent *storey*.	(1) (2) (3) (7)
4	**In-plane Discontinuity in vertical lateral force-resisting element** An in-plane offset of a lateral load-resisting element of the SFRS or a reduction in lateral stiffness of the resisting element in the *storey* below.	(1) (2) (3) (7)
5	**Out-of-Plane Offsets** Discontinuities in a lateral force path, such as out-of-plane offsets of the vertical elements of the SFRS.	(1) (2) (3) (7)
6	**Discontinuity in Capacity - Weak Storey** A weak *storey* is one in which the *storey* shear strength is less than that in the *storey* above. The *storey* shear strength is the total strength of all seismic-resisting elements of the SFRS sharing the *storey* shear for the direction under consideration.	(3)
7	**Torsional Sensitivity- to be considered when diaphragms are not flexible.** Torsional sensitivity shall be considered to exist when the ratio B calculated according to Sentence 4.1.8.11(9) exceeds 1.7.	(1) (3) (4) (7)
8	**Non-orthogonal Systems** A “Non-orthogonal System” irregularity shall be considered to exist when the SFRS is not oriented along a set of orthogonal axes.	(5) (7)

Vertical 1 - Soft Story

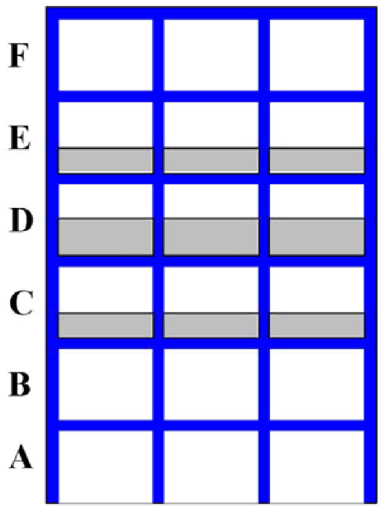


$$K_C < 0.70 \cdot K_D$$

or

$$K_C < 0.80 \frac{(K_D + K_E + K_F)}{3}$$

Vertical 2 - Mass Distribution

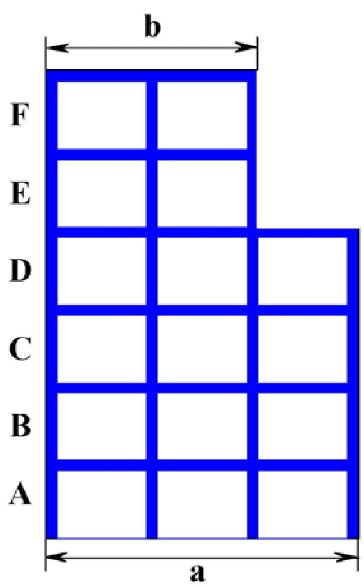


$w_D > 1.50 \cdot w_E$

or

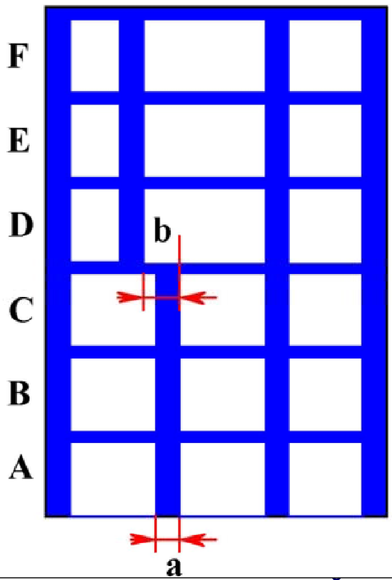
$w_D > 1.50 \cdot w_C$

Vertical 3 - Geometric Irregularity



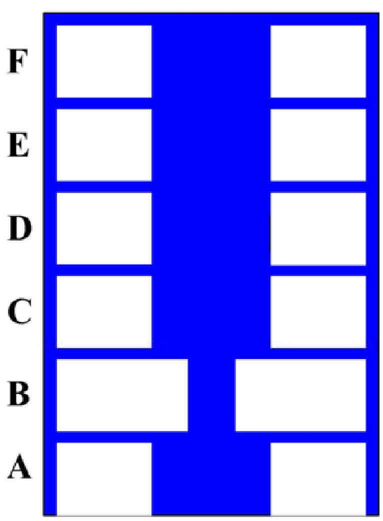
$a > 1.30b$

Vertical 4 - In-Plane Displacement



b > a

Vertical 5 - Weak Story

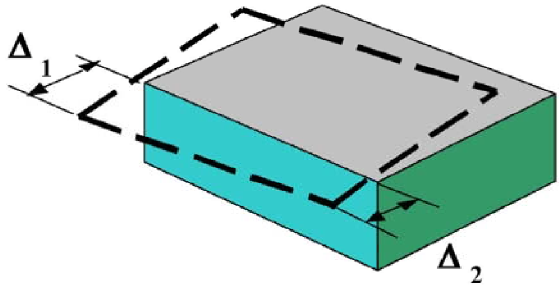


Strength B

<

0.70· Strength C

Plan 1 - Torsional Irregularity



$$\Delta_1 > 1.7\left(\frac{\Delta_1 + \Delta_2}{2}\right)$$

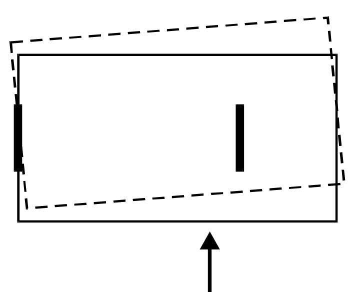
7 Torsional sensitivity

if the ratio B > 1.7.

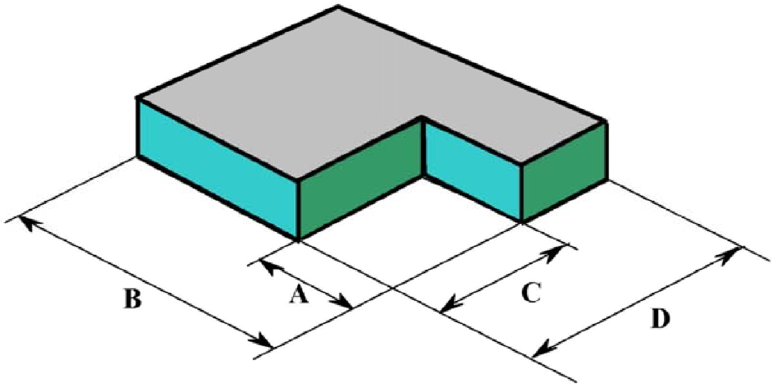
$B = \delta_{max} / \delta_{avg}$

δ calculated for static loads applied at $\pm$ 0.10 D_n

Plan

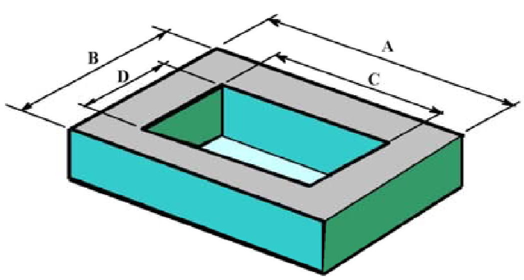


Plan 2 - Setbacks

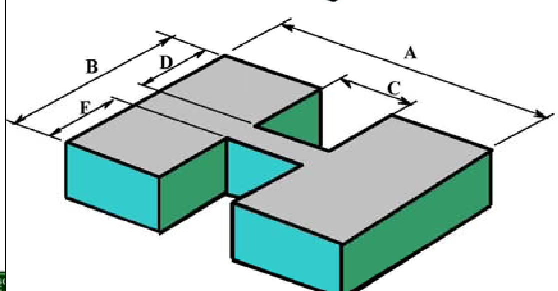


$$A > 0.15 \cdot B \quad \text{or} \quad C > 0.15 \cdot D$$

Plan 3 - Diaphragm Irregularities

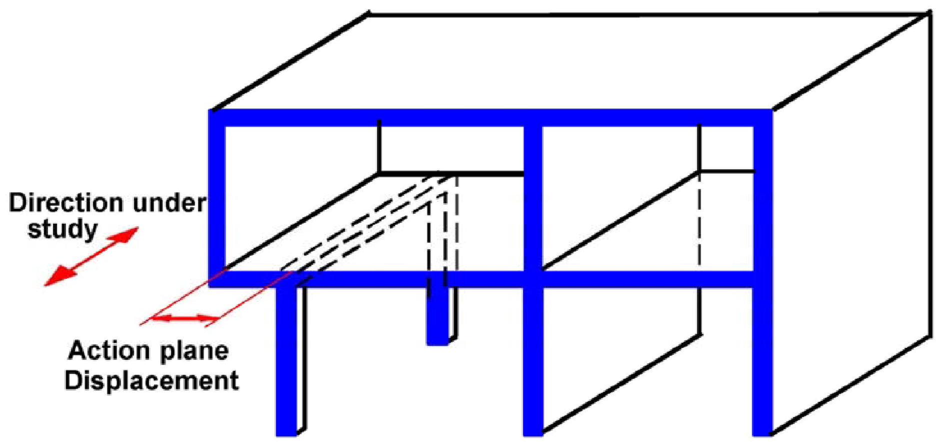


$$C \cdot D > 0.5 \cdot A \cdot B$$

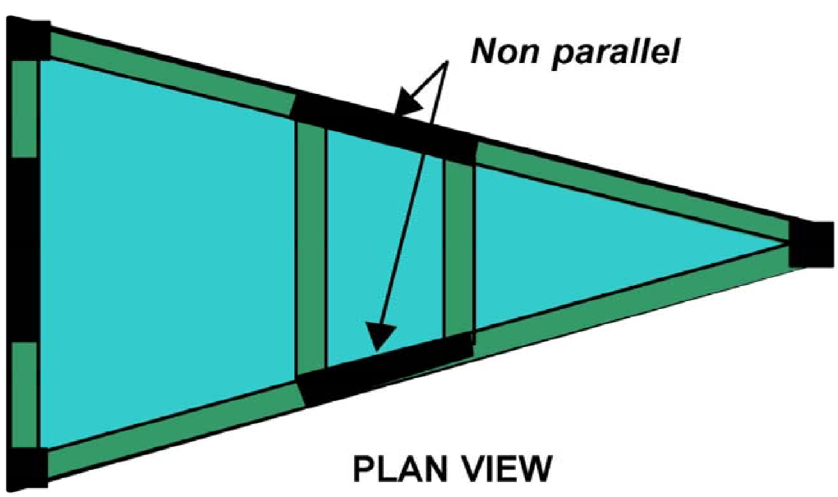


$$(C \cdot D + C \cdot E) > 0.5 \cdot A \cdot B$$

Plan 4 - Action Plane Displacement



Plan 5 - Non-Parallel Systems



4.1.8.8. Direction of Loading

Earthquake forces shall be assumed to act in any horizontal direction, except that the following shall be considered to provide adequate design force levels in the structure:

a) Where components of the SFRS are oriented along a set of orthogonal axes, independent analyses about each of the principal axes of the structure shall be performed.

b) Where the components of the SFRS are not oriented along a set of orthogonal axes and IEFaSa(0.2) is less than 0.35, independent analyses about any two orthogonal axes is permitted.

c) When the components of the SFRS are not oriented along a set of orthogonal axes and IEFaSa(0.2) is equal to or greater than 0.35, analysis of the structure independently in any two orthogonal directions for 100% of the prescribed earthquake loads applied in one direction plus 30% of the prescribed earthquake loads in the perpendicular direction with the combination requiring the greater element strength being used in the design.

STRUCTURAL IRREGULARITIES

- Irregularity Type 8 – “Non-orthogonal lateral force resisting system”
- If $I_E F_a S_{a(0.2)} \geq 0.35$ (about 1/3 of Vancouver value), then:
  - pick any orthogonal set of axes.
  - analyse for 100% of base shear along each axis concurrent with 30% of the base shear along the other axis.

THREE-DIMENSIONAL COMPUTER MODEL

- Real and accidental torsional effects must be considered for all structures. Therefore, all structures must be treated as three-dimensional systems.
- Structures with irregular plans, vertical setbacks or soft stories will cause no additional problems if a realistic three-dimensional computer model is created.
- This model should be developed in the very early stages of design because it can be used for static wind and vertical loads, as well as dynamic seismic loads.
- Only structural elements with significant stiffness and ductility should be modeled. Non-structural brittle components can be neglected. However, shearing, axial deformations and non-center line dimensions can be considered in all members without a significant increase in computational effort by most modern computer programs.
- The rigid, in-plane approximation of floor systems has been shown to be acceptable for most buildings. For the purpose of elastic dynamic analysis, gross concrete sections are normally used, neglecting the stiffness of the steel. A cracked section mode should be used to check the final design.

THREE-DIMENSIONAL COMPUTER MODEL

The P-Delta effects should be included in all structural models. The effect of including P-Delta displacements in a dynamic analysis results in a small increase in the period of all modes.

In addition to being more accurate, an additional advantage of automatically including P-Delta effects is that the moment magnification factor for all members can be taken as unity in all subsequent stress checks.

The mass of the structure can be estimated with a high degree of accuracy. The major assumption required is to estimate the amount of live load to be included as added mass.

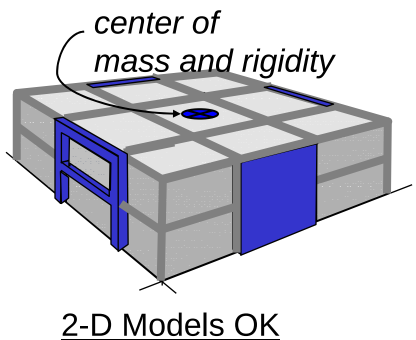
The lumped mass approximation has proven to be accurate. In the case of the rigid diaphragm approximation, the rotational mass moment of inertia must be calculated.

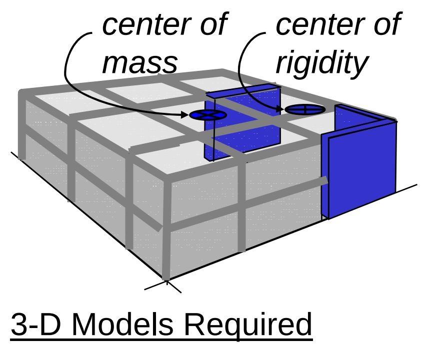
The stiffness of the foundation region of most structures can be modeled using massless structural elements. It is particularly important to model the stiffness of piles and the rotational stiffness at the base of shear walls.

The computer model for static loads only should be executed before conducting a dynamic analysis. Equilibrium can be checked and various modeling approximations can be verified using simple static load patterns. The results of a dynamic analysis are generally very complex and the forces obtained from a response spectra analysis are always positive. Therefore, dynamic equilibrium is almost impossible to check. However, it is relatively simple to check energy balances in both linear and nonlinear analysis.

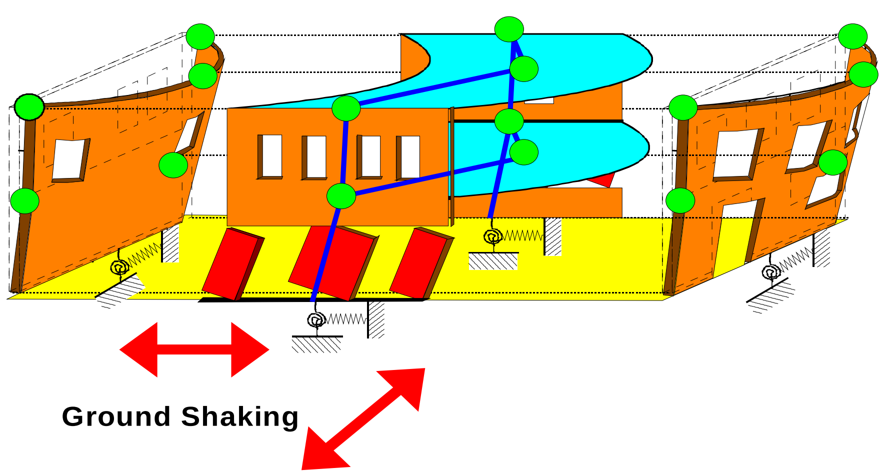
2-D versus 3-D Models

- 2D models adequate for structures with reasonably balanced mass and stiffness distributions.
- If center of mass and center of rigidity do not match, torsional response results, so 3D models are needed.





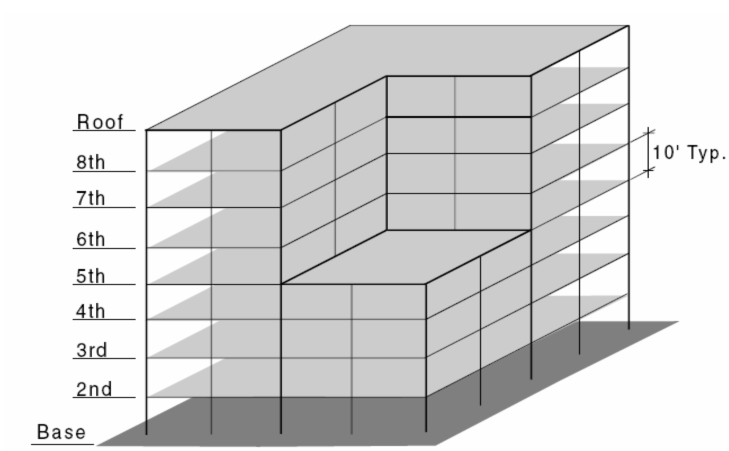
Analysis Idealizations



3D models:

The current code defines an “irregular structure” as one that has a certain geometric shape or in which stiffness and mass discontinuities exist. A far more rational definition is that a “regular structure” is one in which there is a minimum coupling between the lateral displacements and the torsional rotations for the mode shapes associated with the lower frequencies of the system. Therefore, if the model is modified and “tuned” by studying the three-dimensional mode shapes during the preliminary design phase, it may be possible to convert a “geometrically irregular” structure to a “dynamically regular” structure from an earthquake-resistant design standpoint.

Example of 3D analysis



Three Dimensional Base Forces and Moments

MODE	PERIOD	MODAL BASE SHEAR REACTIONS			MODAL OVERTURNING MOMENTS		
	Seconds	X-DIR	Y-DIR	Angle Deg.	X-AXIS	Y-AXIS	Z-AXIS
1	.6315	.781	.624	38.64	-37.3	46.6	-18.9
2	.6034	-.624	.781	-51.37	-46.3	-37.0	38.3
3	**.3501**	**.785**	**.620**	**38.30**	**-31.9**	**40.2**	**85.6**
4	.1144	-.753	-.658	41.12	12.0	-13.7	7.2
5	.1135	.657	-.754	-48.89	13.6	11.9	-38.7
6	**.0706**	**.989**	**.147**	**8.43**	**-33.5**	**51.9**	**2438.3**
7	.0394	-.191	.982	-79.01	-10.4	-2.0	29.4
8	.0394	-.983	-.185	10.67	1.9	-10.4	26.9
9	**.0242**	**.848**	**.530**	**32.01**	**-5.6**	**8.5**	**277.9**
10	.0210	.739	.673	42.32	-5.3	5.8	-3.8
11	.0209	.672	-.740	-47.76	5.8	5.2	-39.0
12	**.0130**	**-.579**	**.815**	**-54.63**	**-.8**	**-8.8**	**-1391.9**
13	.0122	.683	.730	46.89	-4.4	4.1	-6.1
14	.0122	.730	-.683	-43.10	4.1	4.4	-40.2
15	.0087	-.132	-.991	82.40	5.2	-.7	-22.8
16	.0087	-.991	.135	-7.76	-.7	-5.2	30.8
17	**.0074**	**-.724**	**-.690**	**43.64**	**4.0**	**-4.2**	**-252.4**
18	.0063	-.745	-.667	41.86	3.1	-3.5	7.8
19	.0062	-.667	.745	-48.14	-3.5	-3.1	38.5
20	.0056	-.776	-.630	39.09	2.8	-3.4	54.1
21	.0055	-.630	.777	-50.96	-3.4	-2.8	38.6
22	.0052	.776	.631	39.15	-2.9	3.5	66.9
23	**.0038**	**-.766**	**-.643**	**40.02**	**3.0**	**-3.6**	**-323.4**
24	**.0034**	**-.771**	**-.637**	**39.58**	**2.9**	**-3.5**	**-436.7**

Three Dimensional Participating Mass - (percent)

MODE	X-DIR	Y-DIR	Z-DIR	X-SUM	Y-SUM	Z-SUM
1	34.224	21.875	.000	34.224	21.875	.000
2	23.126	36.212	.000	57.350	58.087	.000
3	2.003	1.249	.000	59.354	59.336	.000
4	13.106	9.987	.000	72.460	69.323	.000
5	9.974	13.102	.000	82.434	82.425	.000
6	.002	.000	.000	82.436	82.425	.000
7	.293	17.770	.000	82.729	90.194	.000
8	7.726	.274	.000	90.455	90.469	.000
9	.039	.015	.000	90.494	90.484	.000
10	2.382	1.974	.000	92.876	92.458	.000
11	1.955	2.370	.000	94.831	94.828	.000
12	.000	.001	.000	94.831	94.829	.000
13	1.113	1.271	.000	95.945	96.100	.000
14	1.276	1.117	.000	97.220	97.217	.000
15	.028	1.556	.000	97.248	98.773	.000
16	1.555	.029	.000	98.803	98.802	.000
17	.011	.010	.000	98.814	98.812	.000
18	.503	.403	.000	99.316	99.215	.000
19	.405	.505	.000	99.722	99.720	.000
20	.102	.067	.000	99.824	99.787	.000
21	.111	.169	.000	99.935	99.957	.000
22	.062	.041	.000	99.997	99.998	.000
23	.003	.002	.000	100.000	100.000	.000
24	.001	.000	.000	100.000	100.000	.000

A-4.1.1.5.(2) Structural Equivalents

Sentence 4.1.1.5.(2) provides for the use of design methods not specified in Part 4 of the Code. These include full scale testing and model analogues. Normally this provision is used to permit acceptance of new and innovative structures or to permit acceptance of model tests such as those used to determine structural behavior or snow or wind loads. Sentence 4.1.1.5.(2) specifically requires a level of safety and performance at least equivalent to that provided by design to Part 4 and requires loadings and design requirements to conform to Section 4.1.

Sentence 4.1.1.5.(2) and the provisions for alternative solutions in Division A, Clause 1.2.1.1.(1).(b) are not intended to allow structural design using design standards other than those listed in Part 4. The acceptance of structures that have been designed to other design standards would require the designer to prove to the appropriate authority that the structure provides the level of performance required by Division A, Clause 1.2.1.1.(1).(b). The equivalence of performance can only be established by analyzing the structure for the loads and load factors set out in Section 4.1. and demonstrating that the structure at least meets the requirements of the design standards listed in Sections 4.3. and 4.4.

References & Notes

Anil Chopra, "Dynamics of Structures,"2nd Ed. Prentice Hall, 2001.

Saatcioglu, M. and Humar, J.Donald L. Anderson. "**Dynamic analysis of buildings for earthquake resistant design**," Can. J. Civ. Eng. 30: 338–359 (2003)

Some of the slides included here were kindly provided by Dr. Mete Zosen and Dr. Luis Garcia of Purdue University

Notice

The end