SEAOSC Seismology Committee Webinar
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Analysis and Design for Orthogonal Effects and Multi-Directional Seismic Ground Motion Considering Recent Code Changes

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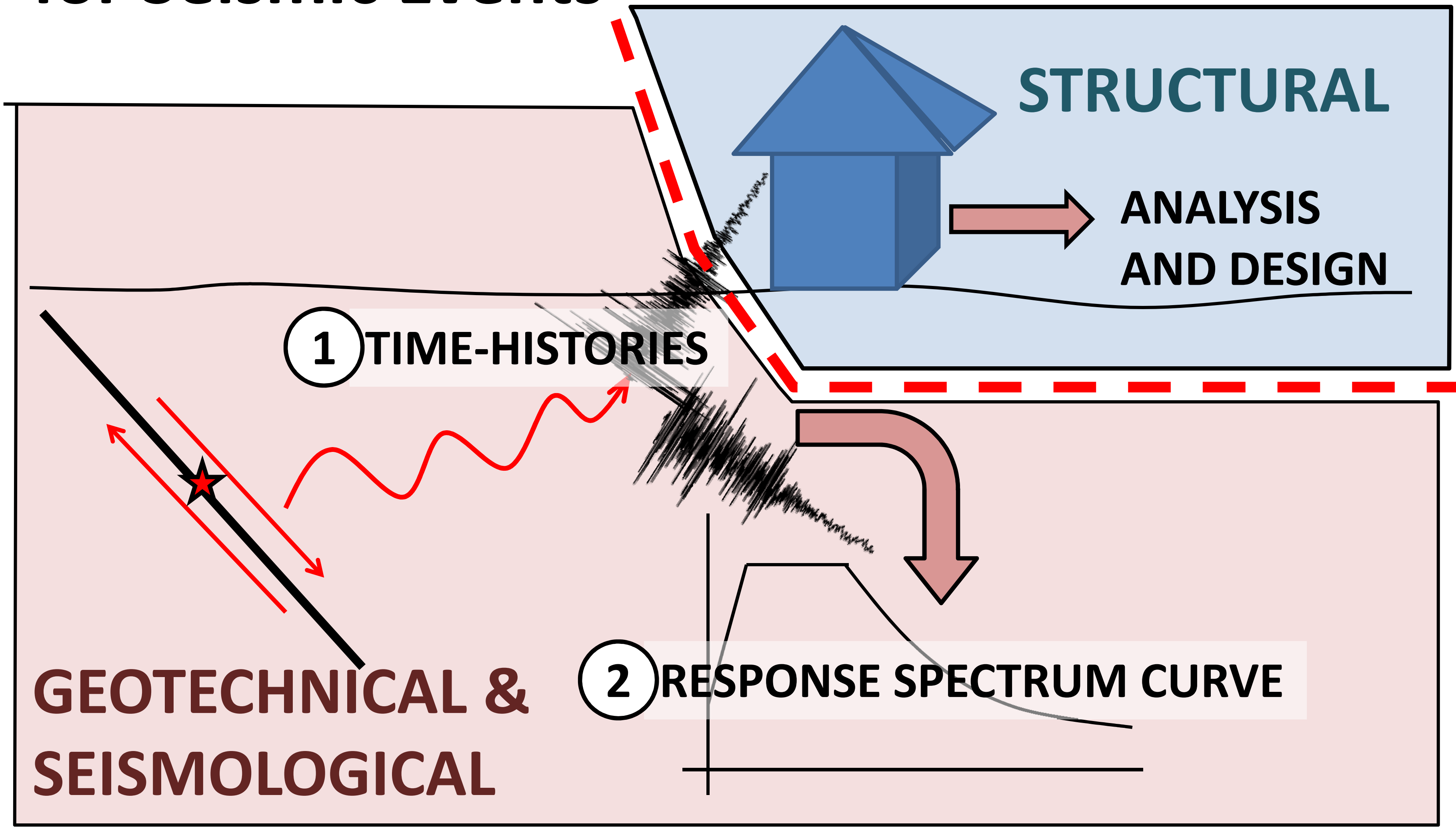
[*currently at Arup, Hong Kong for a long term assignment*]

Outline

- Introduction, Problem Definition
- Response Spectrum (RS) Representations
- Response Spectrum Analysis
  - Modal Combination Procedures
  - Directional Combination Procedures
- Compatibility of RS Representaions and Modal/Directional Combination Procedures
- Review of Some other Issues
- Suggestions for Analysis and Design

Introduction: Analysis and Design for Seismic Events



Problem Definition: Approximations

- There are many "approximations" done on both Geotech/Seism. and Structural Engineering sides of an RS derivation and analysis.

GEOTECH/SEISMOLOGICAL

- All possible earthquakes are represented by a single Response Spectrum (RS) Curve.
- Horizontal ground motion at a given site is represented by a single RS Curve, which is a 2-D motion.

STRUCTURAL ENGINEERING

- RS ANALYSIS requires modal combination rules
- RS ANALYSIS requires directional combination rules
- Peak resultant design member stresses (the direction cannot be known) are estimated from peak displacements for the structures FEM axis directions.

COMPATIBILITY REQUIRED BETWEEN THE TWO FIELDS

Objectives

- To literature review of the procedures used in
  - Derivation of a Response Spectrum curve (Geotech)
  - Response Spectrum Analysis (Structural)
- Review compatibility between

  → Geotechnical and Structural Procedures
- To provide simple guidelines for

  → Conservative analysis and design for multidirectional earthquake and orthogonal effects.

Response Spectrum Representations

- Data: a large set of recorded historical ground motion accelerations are used.

EQ 1 (Acceleration)			EQ 2 (Acceleration)			…	EQ *n* (Acceleration)		
TIME	**X-Dir**	**Y-Dir**	**TIME**	**X-Dir**	**Y-Dir**	…	**TIME**	**X-Dir**	**Y-Dir**
0	0	0	0	0	0		0	0	0
0.005	0.001	-0.005	0.005	0.041	-0.074		0.005	-0.011	0.034
0.010	-0.002	0.004	0.010	0.003	0.002		0.010	0.022	-0.024
…			…				…		
67.000	-0.001	-0.002	45.000	-0.008	0.001		75.000	0.005	0.007

X-Component

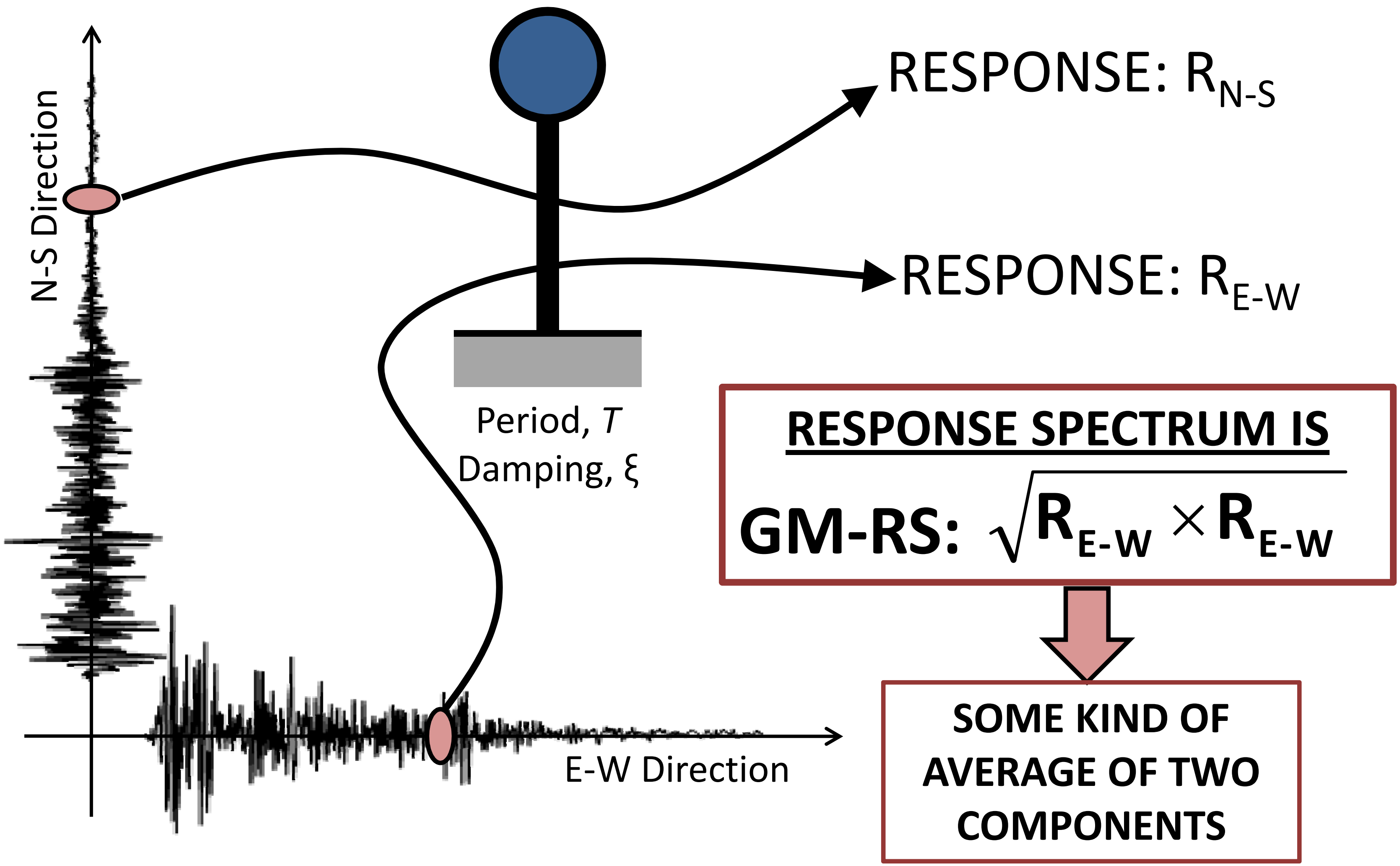
Y-Component

- Some of the Representations….
  - Larger of the two horizontal component
  - Geometric mean of the two horizontal component
  - Arbitrary Horizontal Component
  - Strike Normal, Strike Parallel Component
  - Maximum Rotated

MOST COMMON IN STR. ENG.

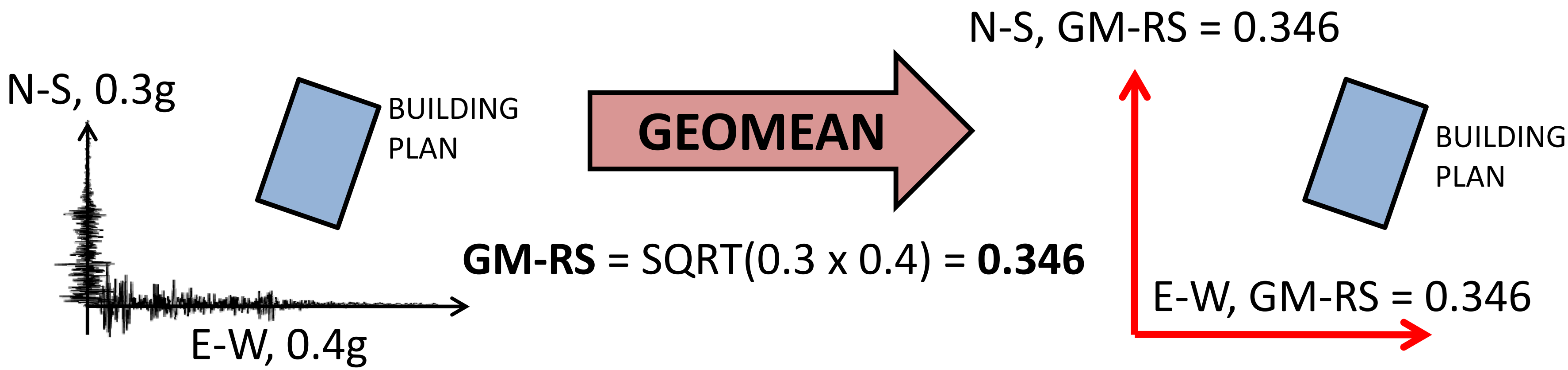
Response Spectrum Representations

- Geomean (<u>in very simple terms</u>):



Response Spectrum Representations

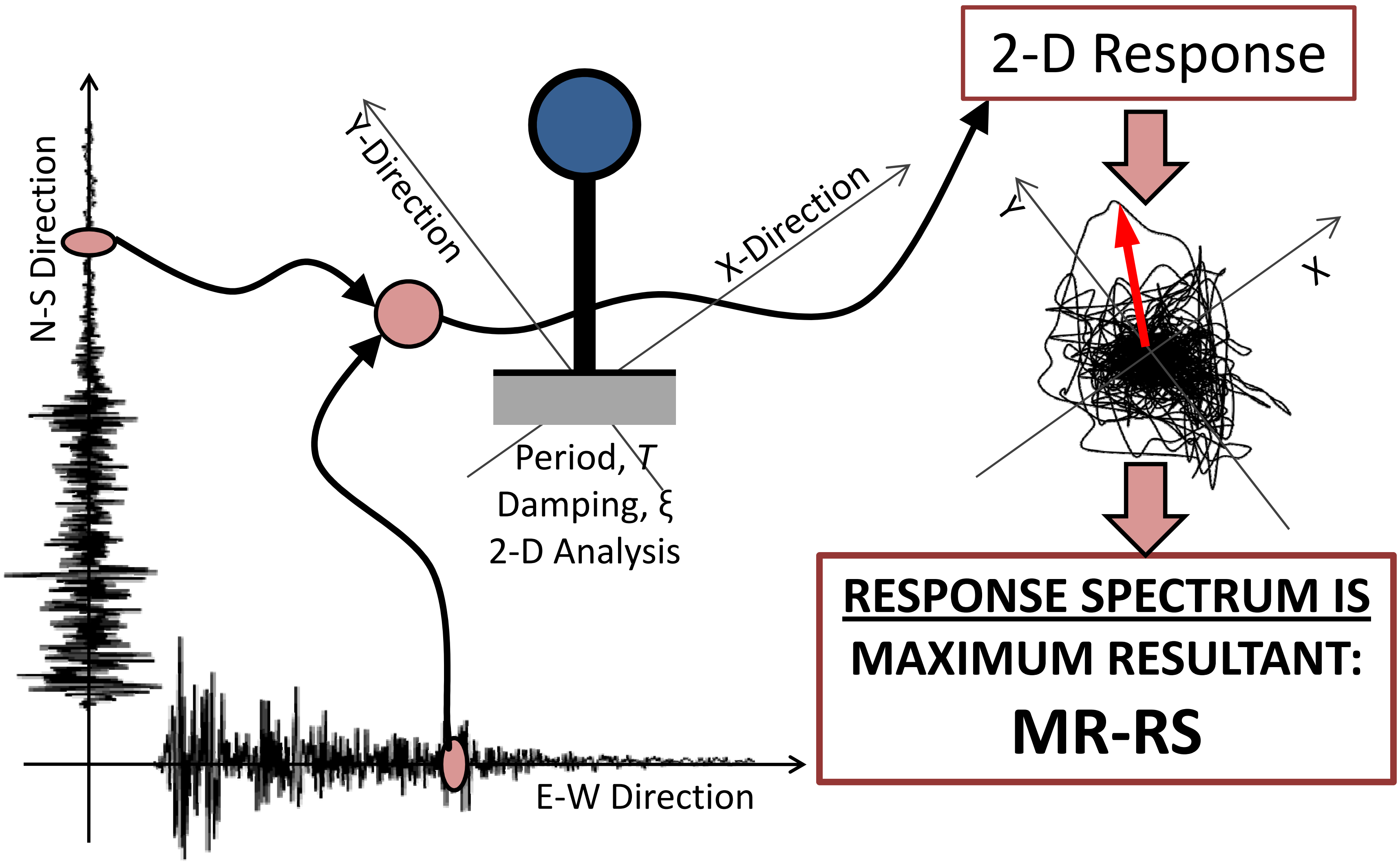
- <u>Geomean Example</u>: Consider a very approximate "back-of-the envelope" type engineering estimation:



- Geomean represents <u>only one component</u> of the seismic effects <u>on the structure</u>; it does not represent the complete seismic effects <u>on the structure</u>.
- The complete seismic effects <u>on the structure</u> can be achieved by applying two Geomean RS curves simultaneously.
- Geomean has been used in ASCE 7-05 and original NGA.

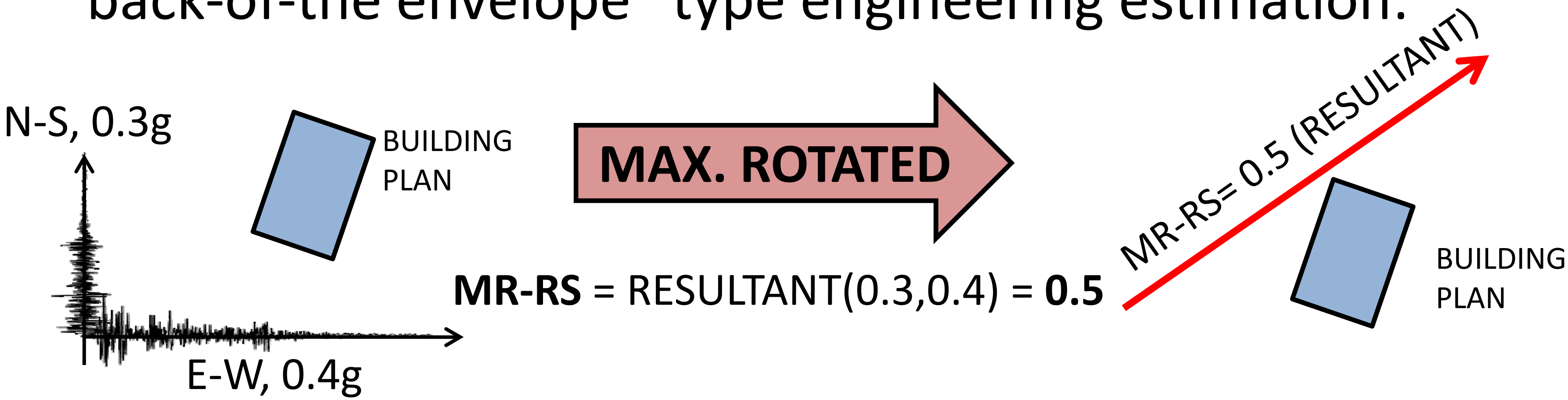
Response Spectrum Representations

- Maximum Rotated (<u>in very simple terms</u>):



Response Spectrum Representations

- Maximum Rotated Example: Consider a very approximate "back-of-the envelope" type engineering estimation:



- Maximum Rotated represents the complete effect of both components of a seismic event on the structure. Therefore, application of one Maximum Rotated RS curve is adequate for structural analysis.
- Maximum Rotated has been used in ASCE 7-10 and amended to NGA.

Response Spectrum Representations

- Comparison: Geomean RS vs Maximum Rotated RS

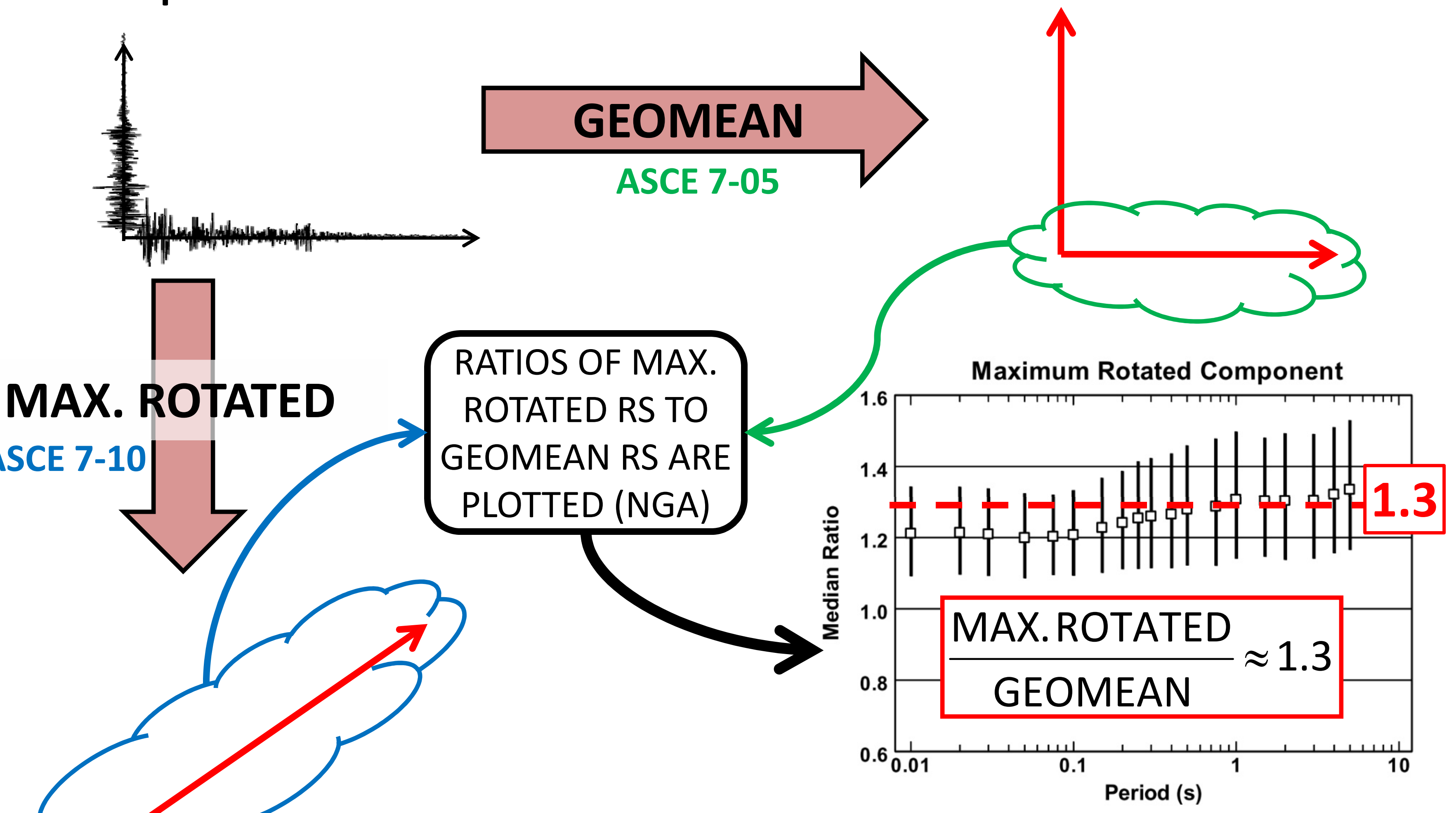


Fig. 4.1 Ratios of alternative horizontal components to new geometric mean.

(Campbell and Bozorgnia, 2007)

Response Spectrum Representations: Codes

ASCE 7-05:
GEOMEAN

ASCE 7-10:
MAX. ROTATED + NGA

HOW IS ASCE 7-05 RELATED TO ASCE 7-10?

- REMEMBER: $\frac{\text{MAX.ROTATED}}{\text{GEOMEAN}} \approx 1.3$
- HOWEVER, **NGA resulted smaller RS values** (for some locations)
- APPROXIMATELY: $\frac{\text{NGA}+\text{MAX.ROTATED}}{\text{GEOMEAN}} \approx 1.0$
- THEREFORE: $\frac{\text{ASCE 7}-\text{10 RS}}{\text{ASCE 7}-\text{05 RS}} \approx 1.0$

REMEMBER:
ASCE 7-10: MAX ROTATED
ASCE 7-05: GEOMEAN

Response Spectrum Represent.: California

ORIGINAL NGA DATABASE

- **NEAR-FIELD EARTHQUAKES (STRONG)**
- **FAR-FIELD EARTHQUAKES (WEAK)**

→ **ORIGINAL NGA & <u>GEOMEAN</u> RESPONSE SPECTRUM**

NEW NGA DB., Huang *et al*. (2008)

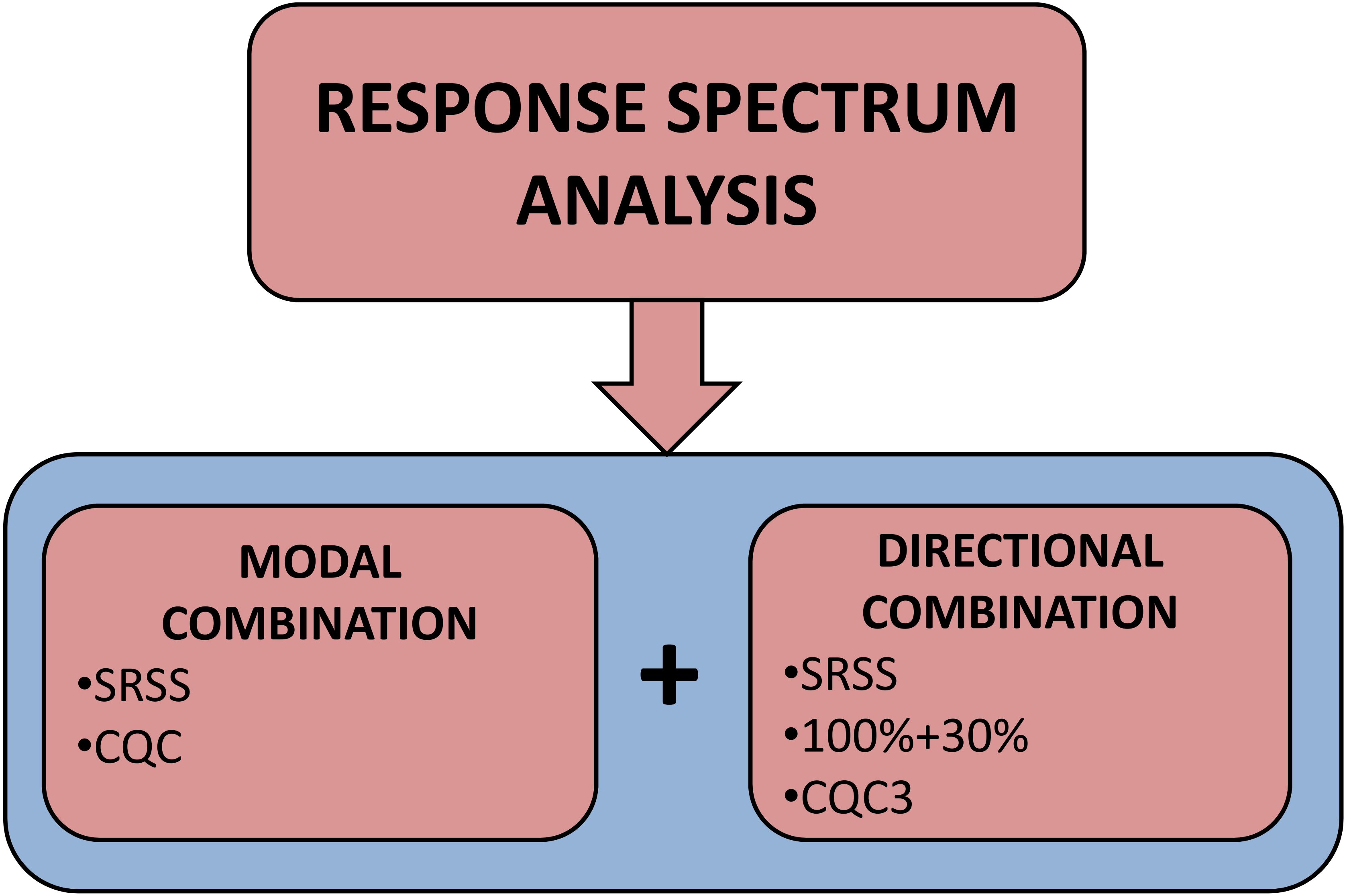
- **NEAR-FIELD EARTHQUAKES (STRONG)**

(FOR REGIONS WITH STRONG SEISMIC ACTIVITY)
E.G.: CALIFORNIA

→ **NGA NEAR FIELD & <u>MAX. ROTATED</u> RESPONSE SPECTRUM**

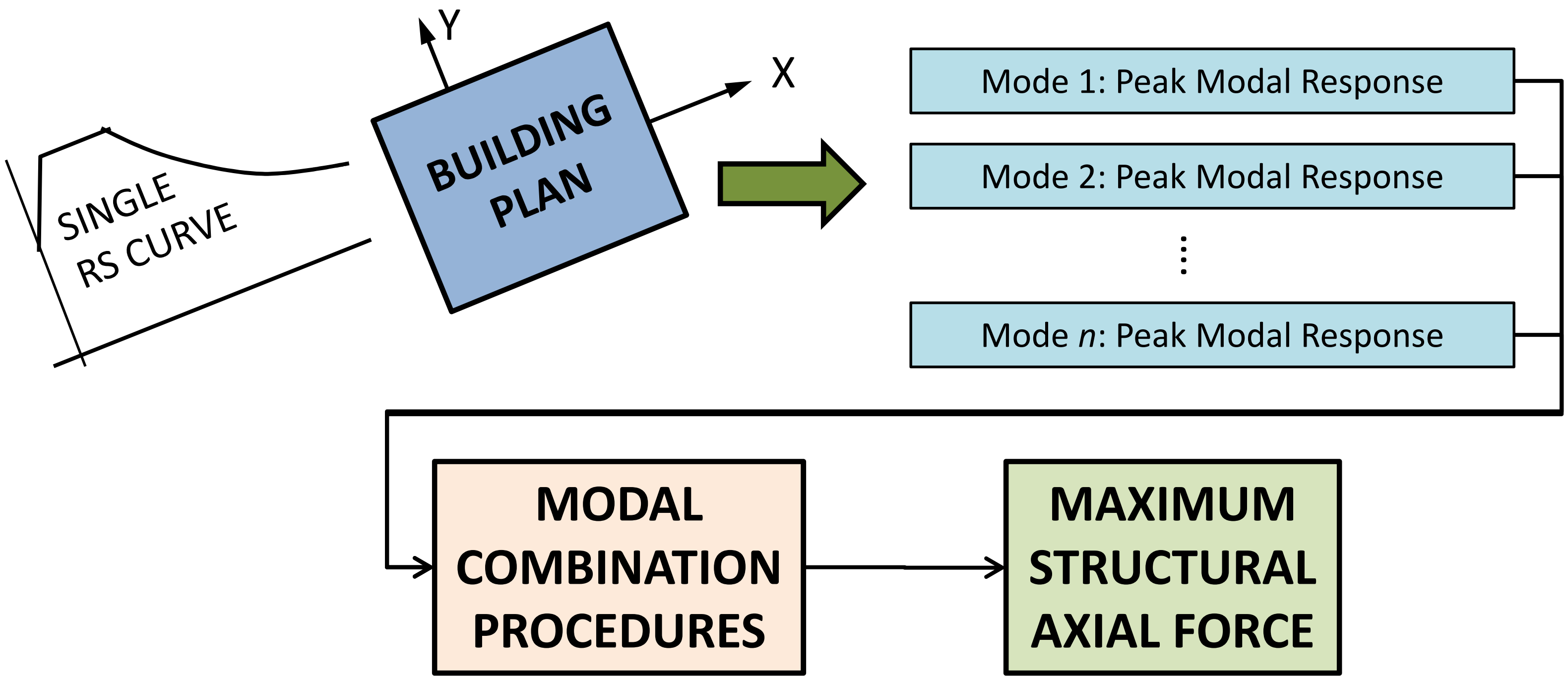
↑ **REQUIRED BY OSHPD, DSA**

Structural Response Spectrum Analysis



Modal Combination Procedures

- <u>ONLY FOR 1-D (single dimension) seismic input applied to building X axis or Y axis</u>



→ SRSS, CQC

Modal Combination Procedures: SRSS

- Square Root of Sum of Squares (SRSS)
- Let R_n = Response value for the n^{th} mode

$$R_{structure} = \text{SQRT}(R_1^2 + R_2^2 + \ldots + R_n^2)$$

- Mostly proven to be OK for structures with well-separated modes
- May have many other drawbacks for a general 3-D structure:
  - Cannot address closely spaced modes (interacting modes)
  - Ignores the signs of modal responses (in/out of phase)

Modal Combination Procedures: CQC

- Complete Quadratic Combination (CQC)
  – Considers relation between the modes using "cross correlation coefficients", which can address
    - <u>Closely spaced modes</u>
    - <u>Signs </u>(+ or -) of the modal responses
- Mostly used in practice: Der Kiureghian (1981) equations

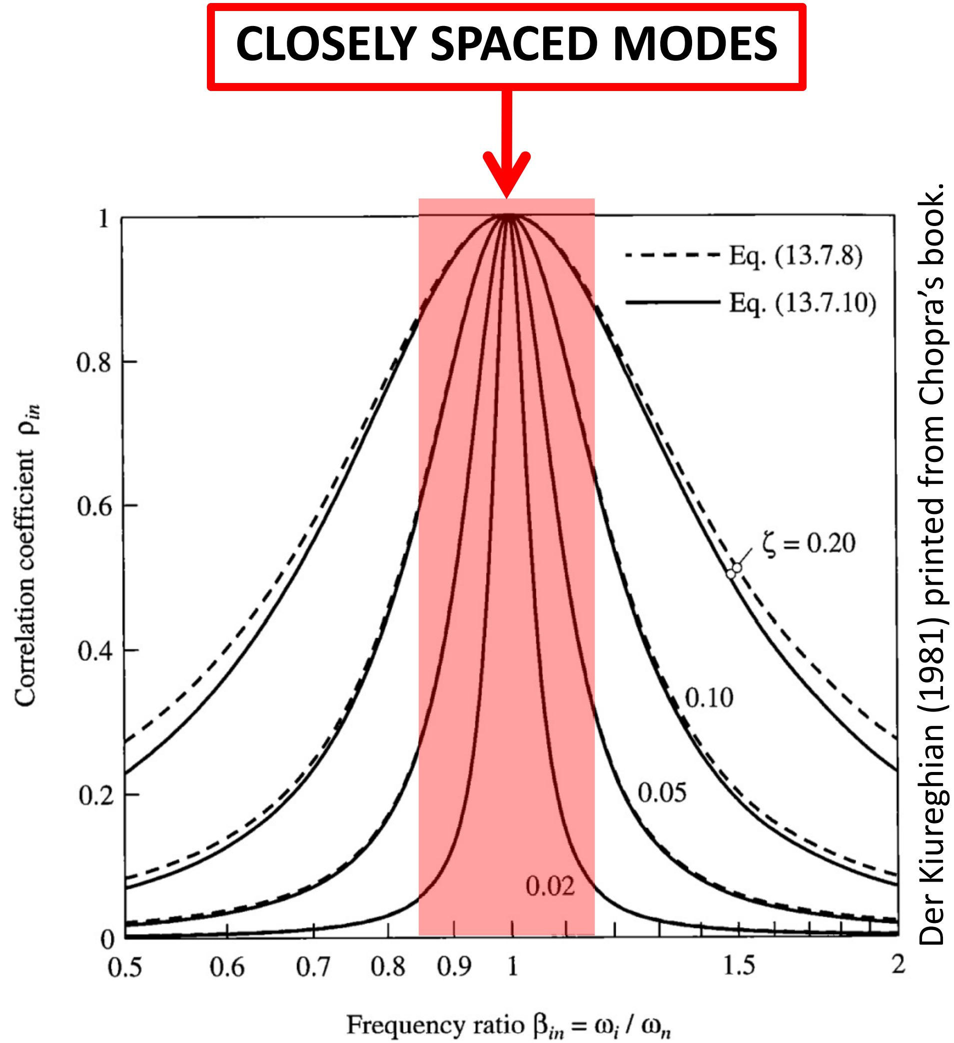
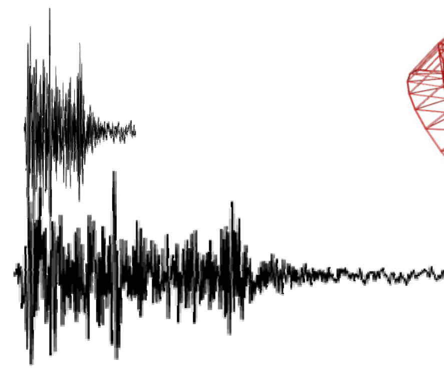
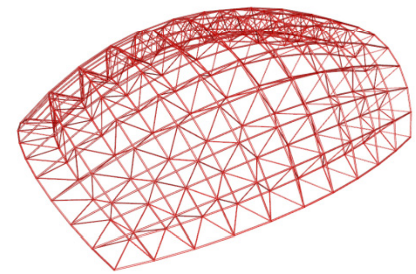


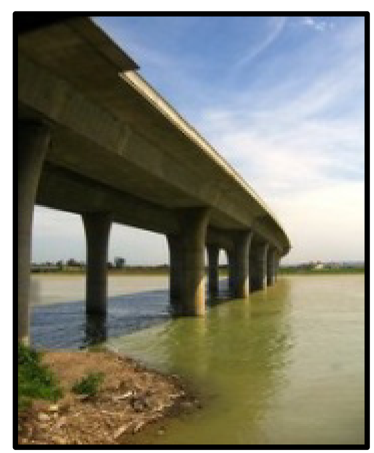
Figure 13.7.1 Variation of correlation coefficient ρ_{in} with modal frequency ratio, $\beta_{in} = \omega_i / \omega_n$, as given by two different equations for four damping values; abcissa scale is logarithmic.

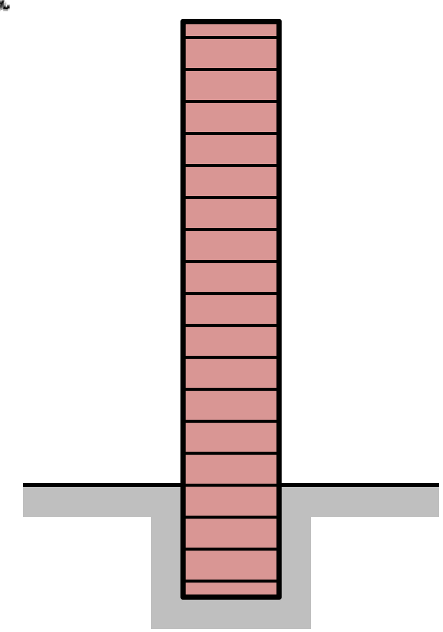
Modal Combination Procedures: CQC

- Der Kiureghian – CQC uses many assumptions (frequently used). Engineers should understand these assumptions in case they do not apply to structure they are analyzing.
  - May not be accurate lightly damped (< 0.5%) structures (e.g.: space truss-type structures)
  - May not be accurate for impulsive, short-duration earthquakes.
  - The structure should have classical mode shapes.
  - The structure should not have sudden and significant changes in its mass, stiffness and damping characteristics.
- If possible, use CQC and avoid SRSS to be on the safe side



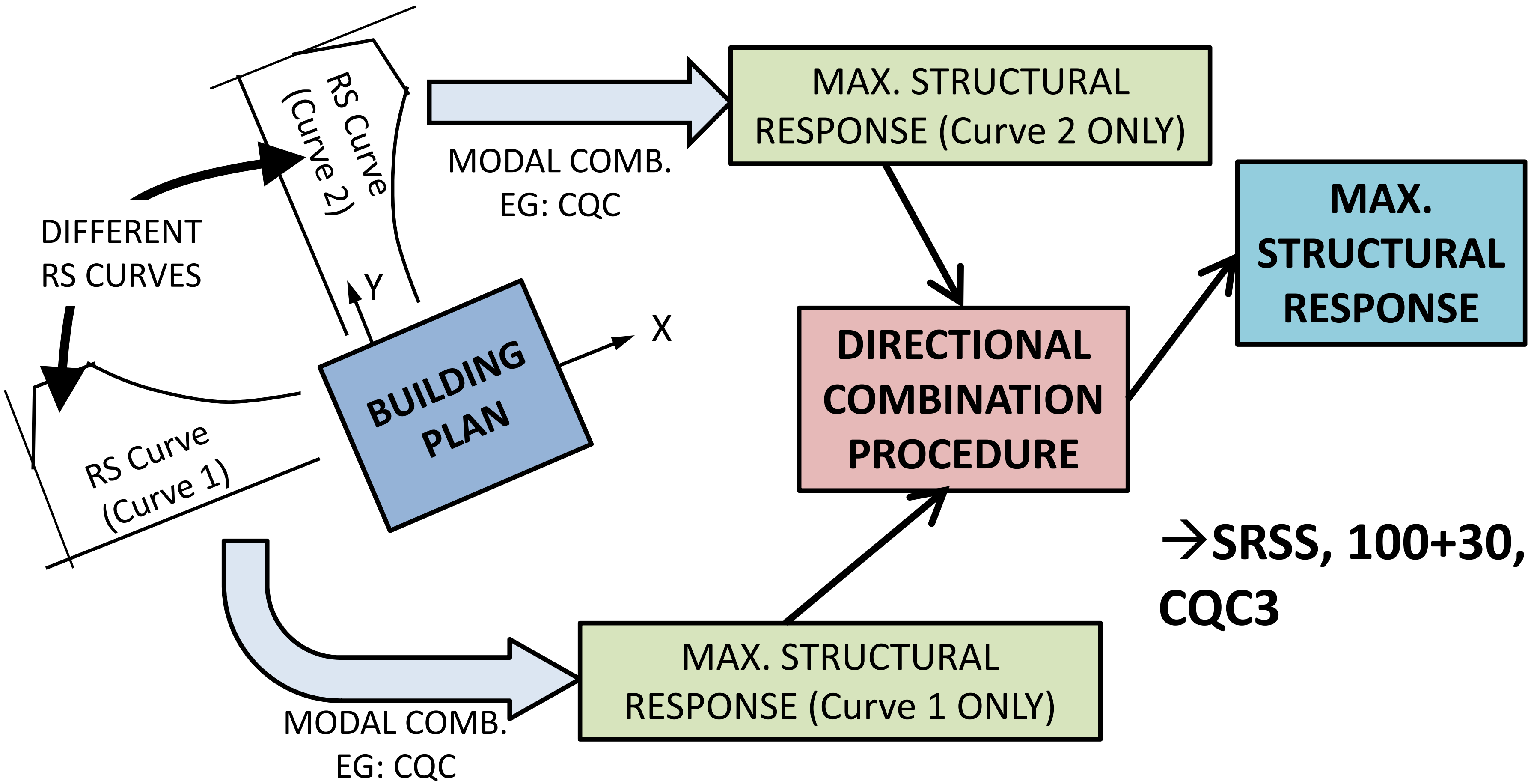






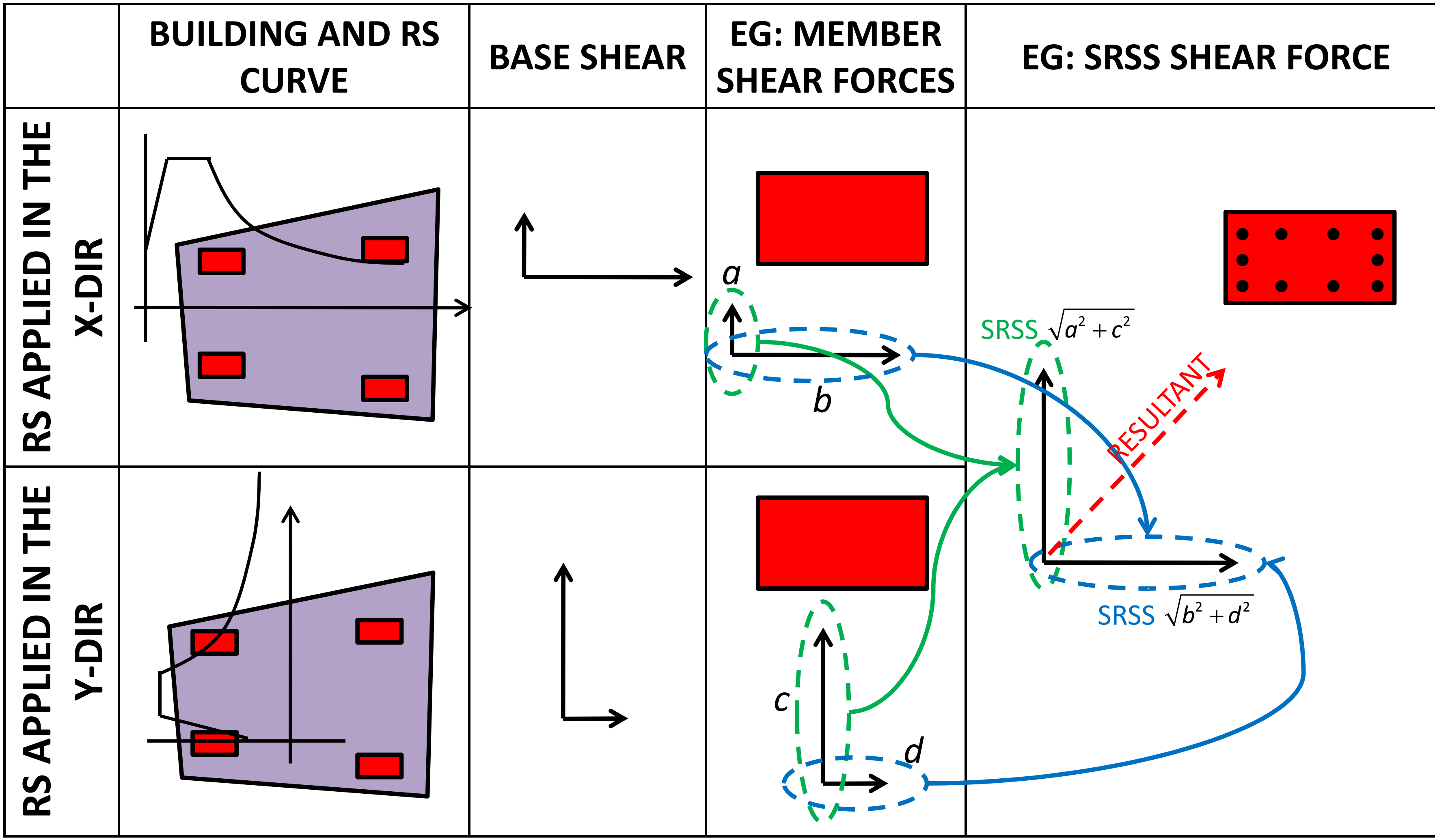
Directional Combination Procedures

- 2-D Seismic Input (two different RS curves) are applied simultaneously to building global axes



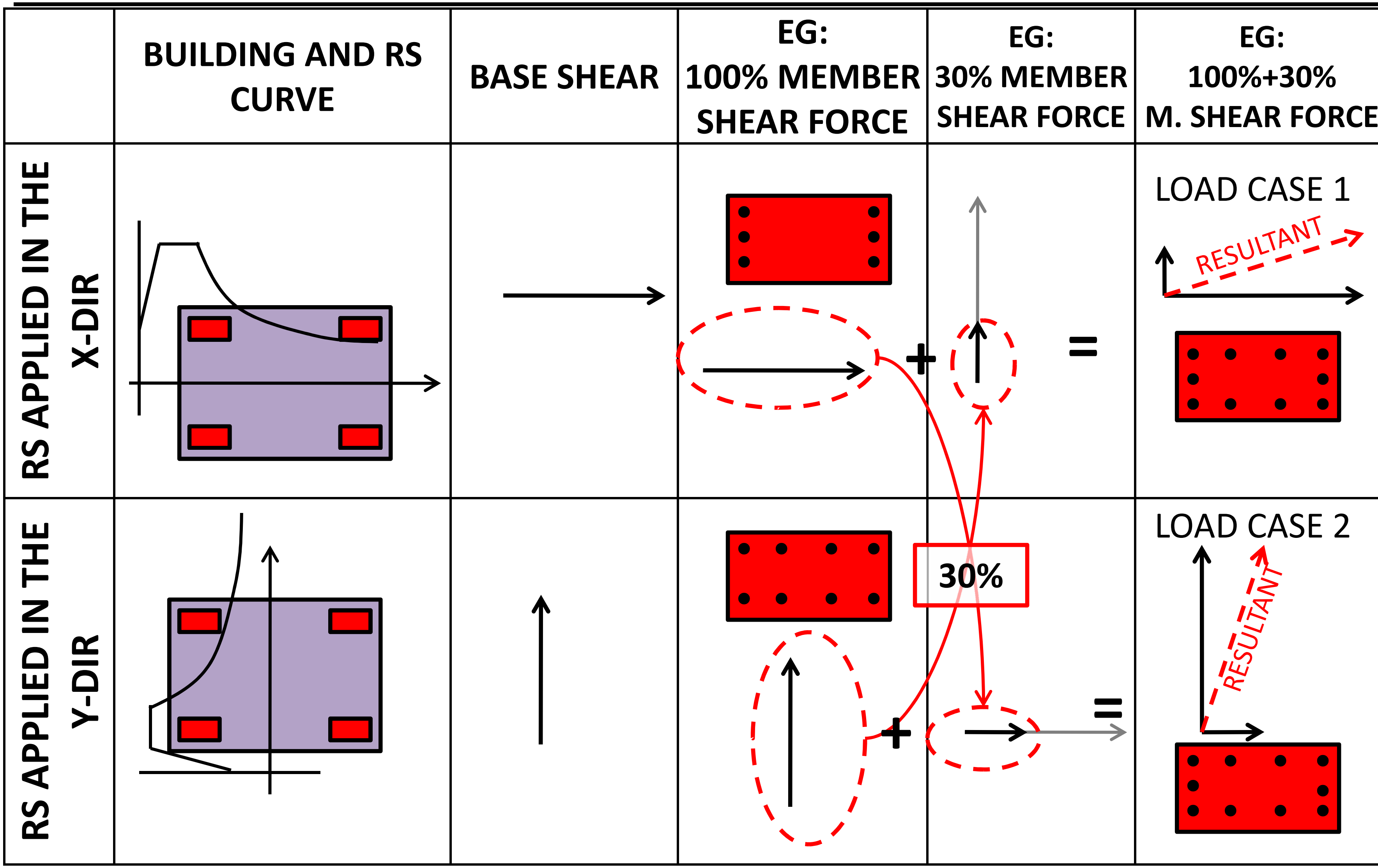
→**SRSS, 100+30, CQC3**

Directional Combination Procedures: SRSS



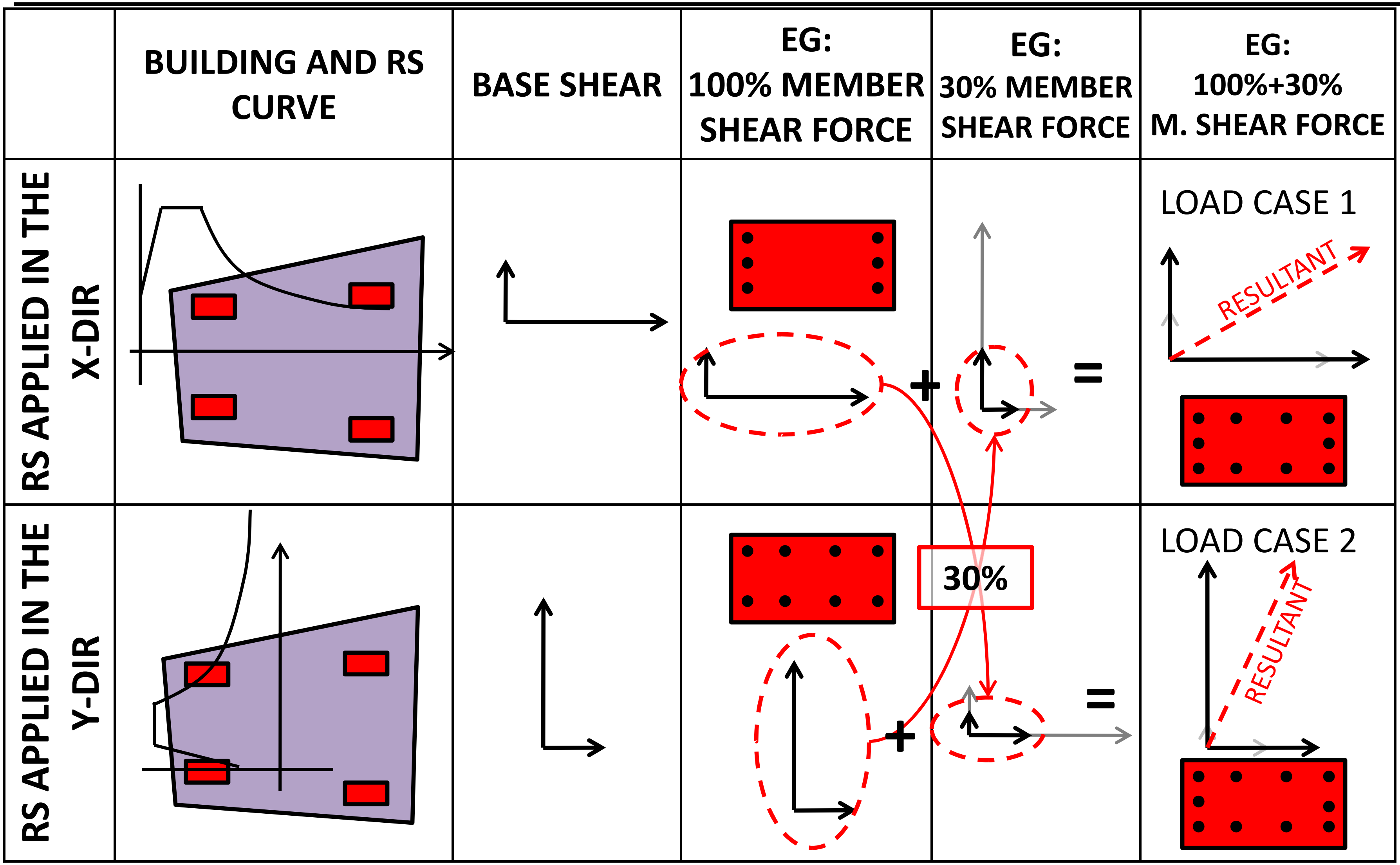
Directional Combination Procedures: 100+30

CONSIDER A PERFECT STRUCTURE: ORTHOGONAL EFFECTS



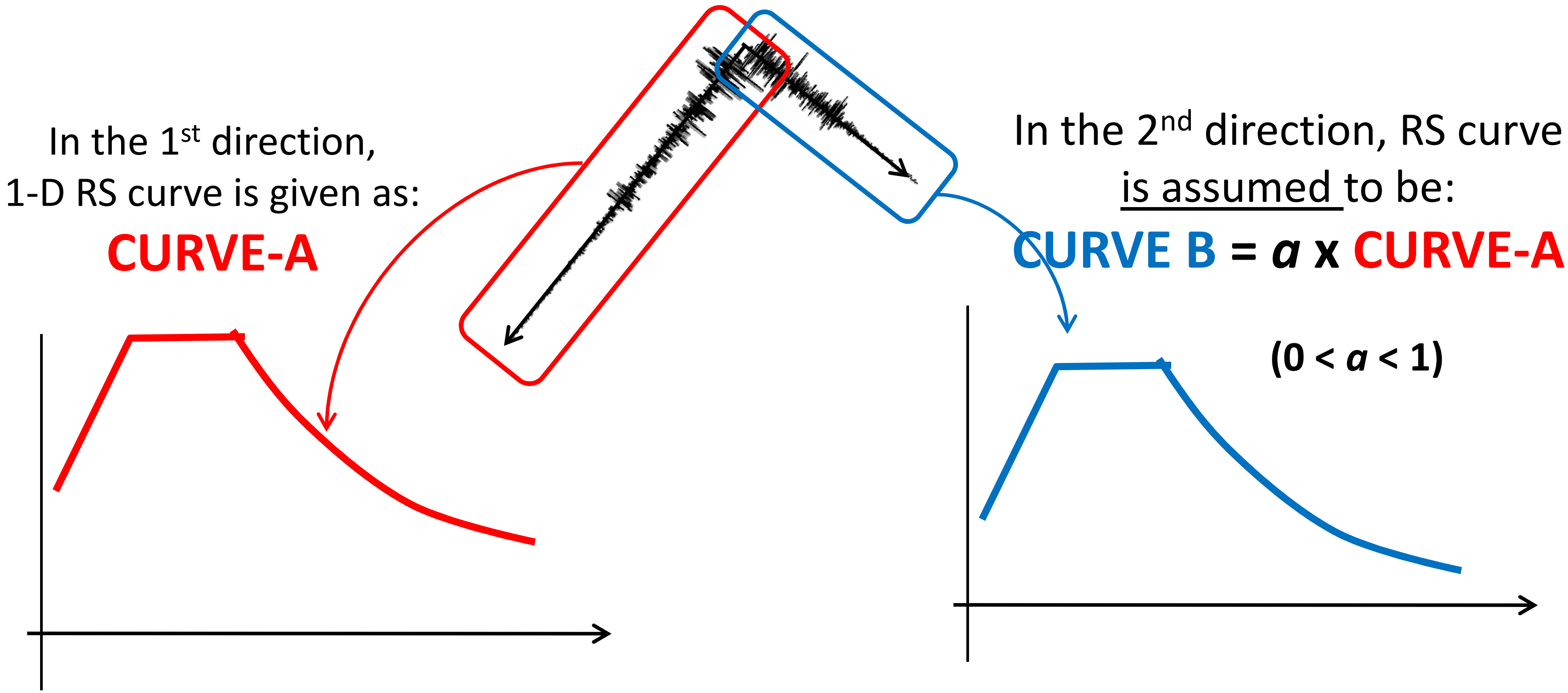
Directional Combination Procedures: 100+30

CONSIDER IRREGULAR STRUCTURE: ORTHOGONAL EFFECTS



Directional Combination Procedures: CQC3

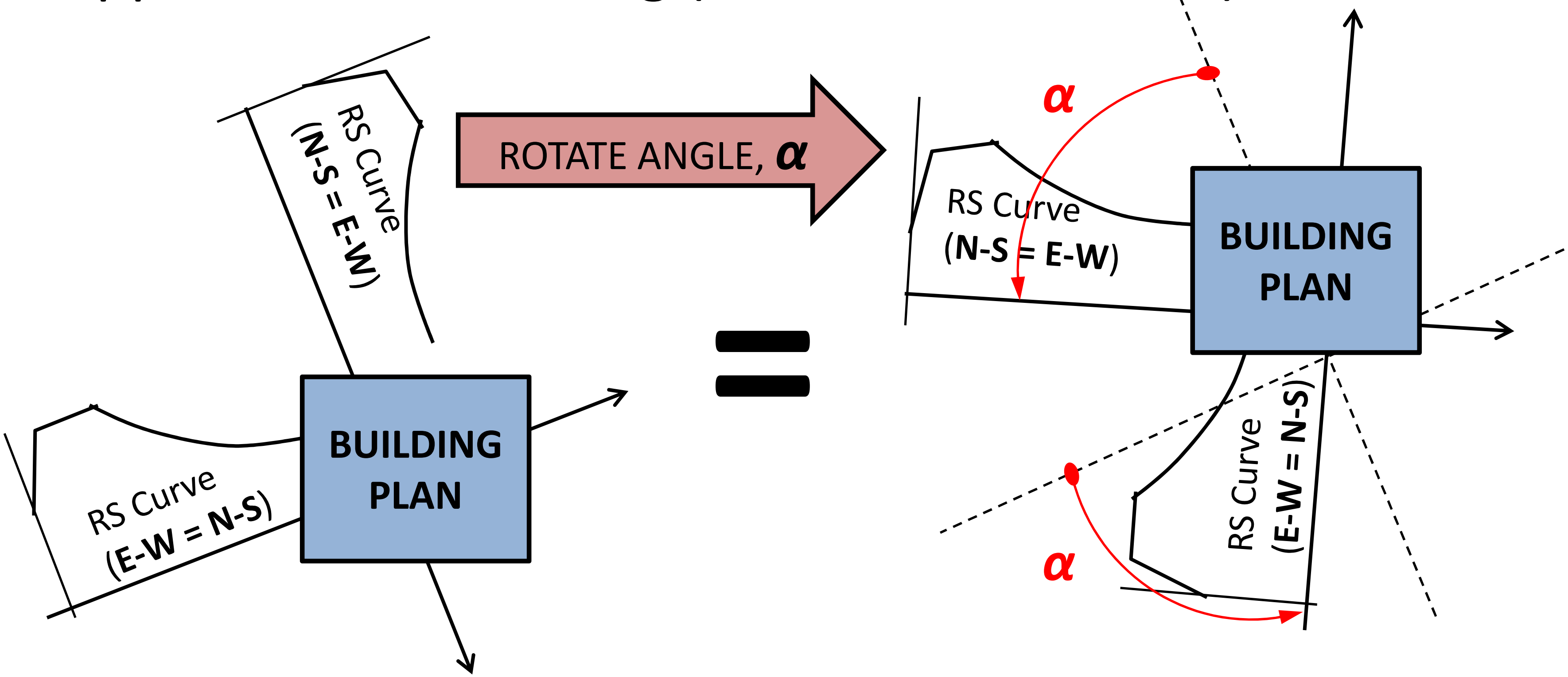
- Assume that the two-dimensional earthquake is as follows:



- In theory, **0 < *a* < 1**. In practice, **0.5 < *a* < 0.85**
- To be able to apply CQC3, the value of "***a***" has to be provided, which is generally not available. Therefore, CQC3 had limited use in practice.
- However, it has another use…..

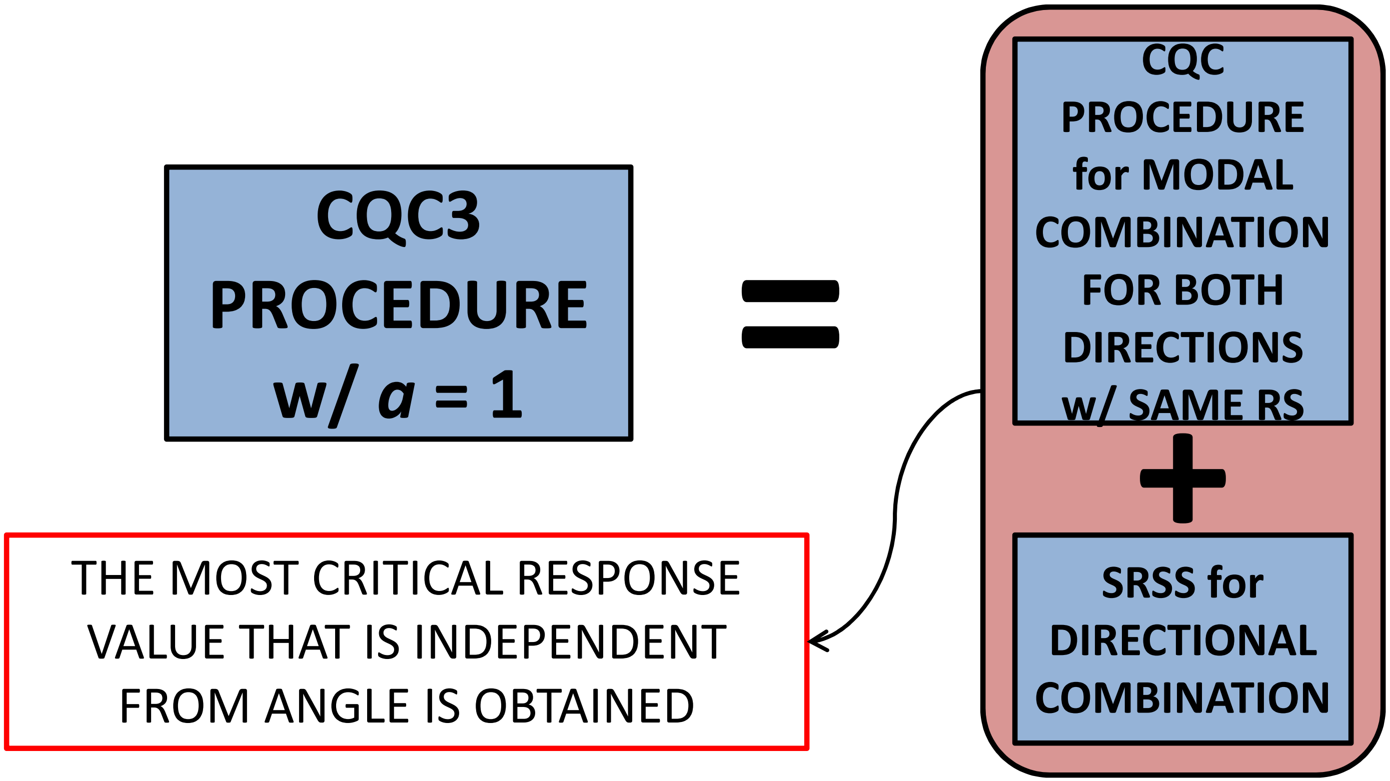
Directional Combination Procedures: CQC3

- CQC3 has an interesting property:
  - (1) If ***a* = 1**, the Response Spectrum analysis results becomes independent of the angle that the RS is applied to the building (Wilson, et al., 1981):



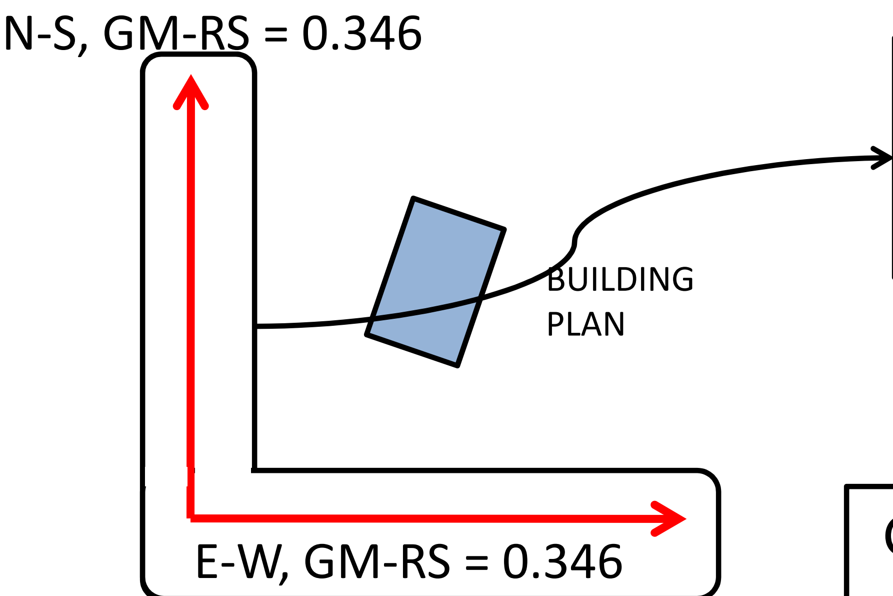
Directional Combination Procedures: CQC3

- CQC3 has an interesting property (cont'd):
  - (2) If ***a* = 1**, the most critical response value IS achieved.
  - (3) If ***a* = 1**, CQC3 is equivalent to CQC + SRSS



Compatibility: CQC3

- Question: What type of RS representation is suitable for CQC3, when ***a*** **= 1**?
- Remember the Geomean RS example shown in the previous slides:



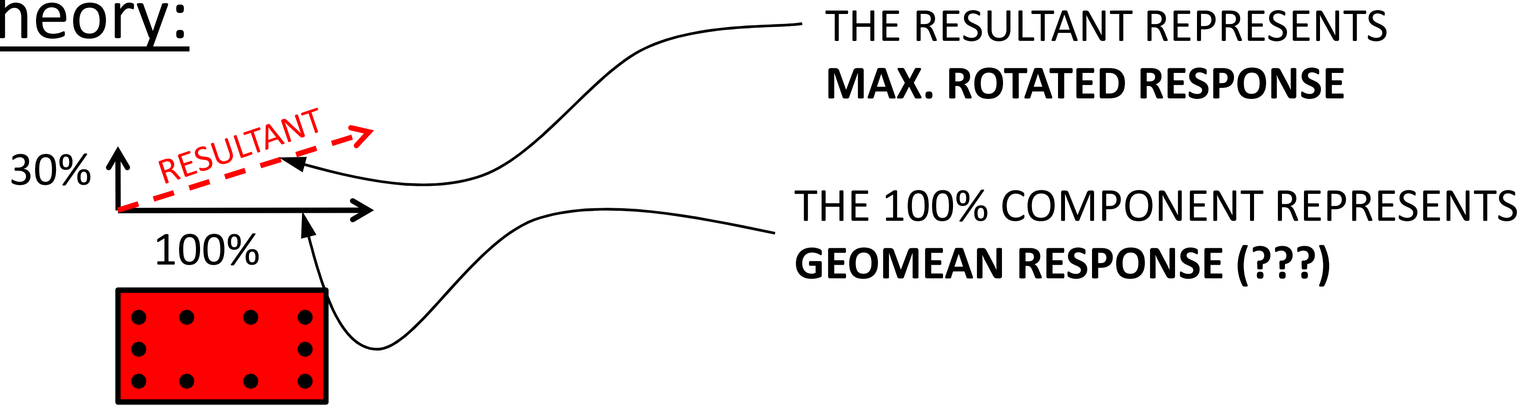
SINCE THE SAME GEOMEAN RS IS USED IN BOTH DIRECTIONS
→ FOR GEOMEAN RS, ***a*** **= 1**

GEOMEAN IS COMPATIBLE WITH CQC3 when ***a*** **=1** (or CQC+SRSS)

Compatibility: Perfect Structure w/ 100 + 30

ASCE 7-10:

In Theory:

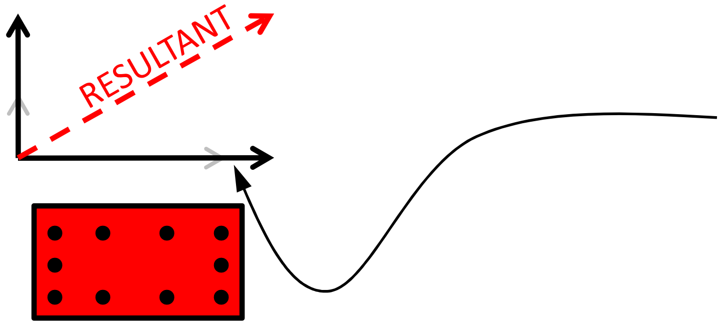


However:

Since RESULTANT ≈ 100% Component, Code is OK.

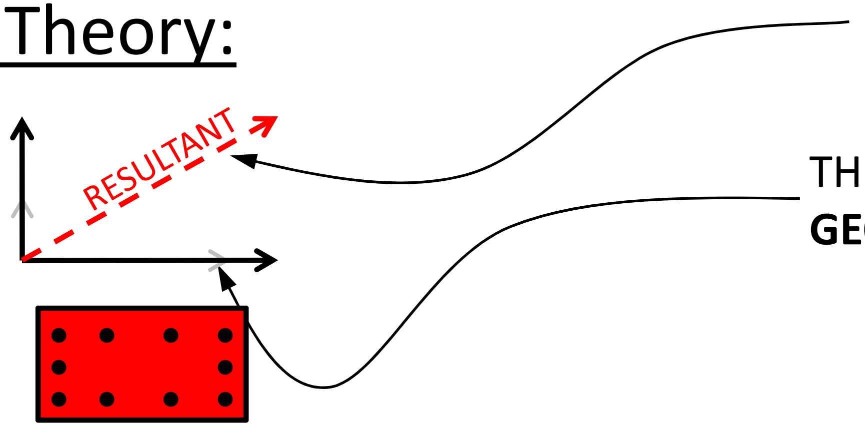
Compatibility: Irregular Struct. w/ 100 + 30

ASCE 7-10:



THE 100% COMPONENT REPRESENTS
MAX. ROTATED RESPONSE

In Theory:



THE RESULTANT REPRESENTS
MAX. ROTATED RESPONSE

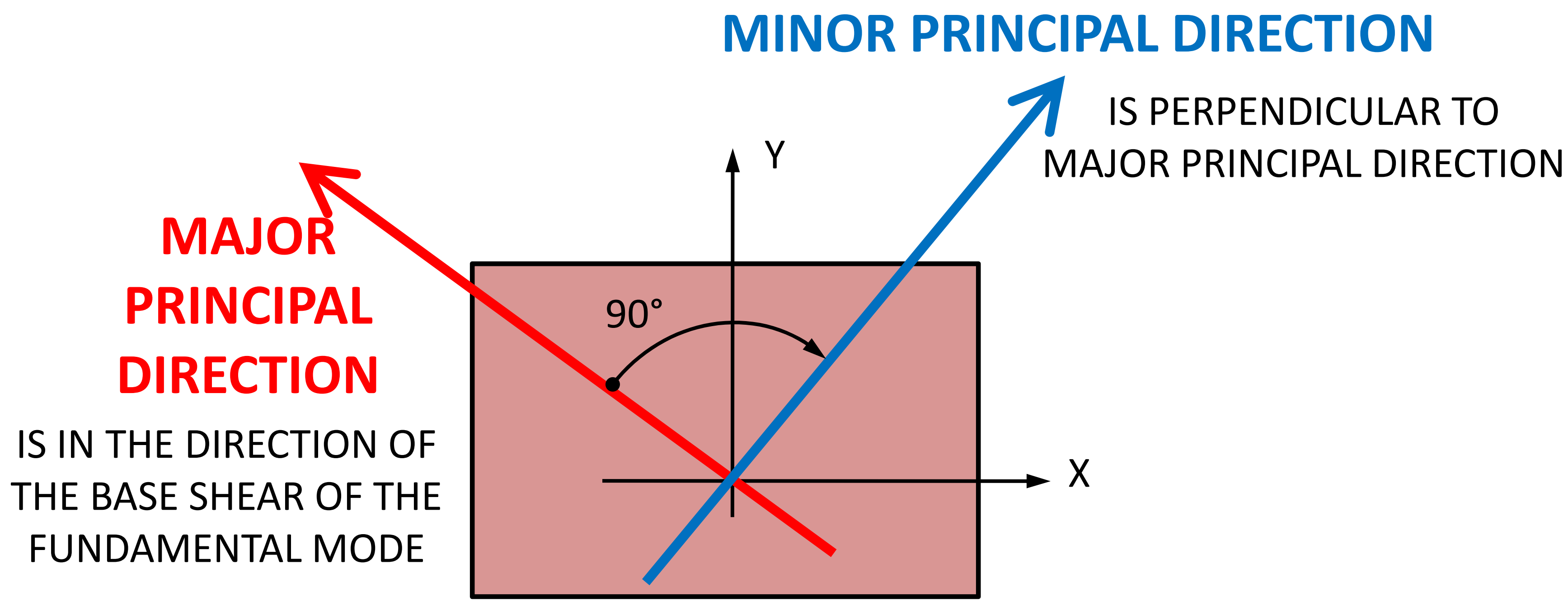
THE 100% COMPONENT REPRESENTS
GEOMEAN RESPONSE (???)

However:

RESULTANT ≠ 100% Component → Code is not CLEAR

Analysis and Design: Suggestions

- Definition of Major and Minor Principal directions:



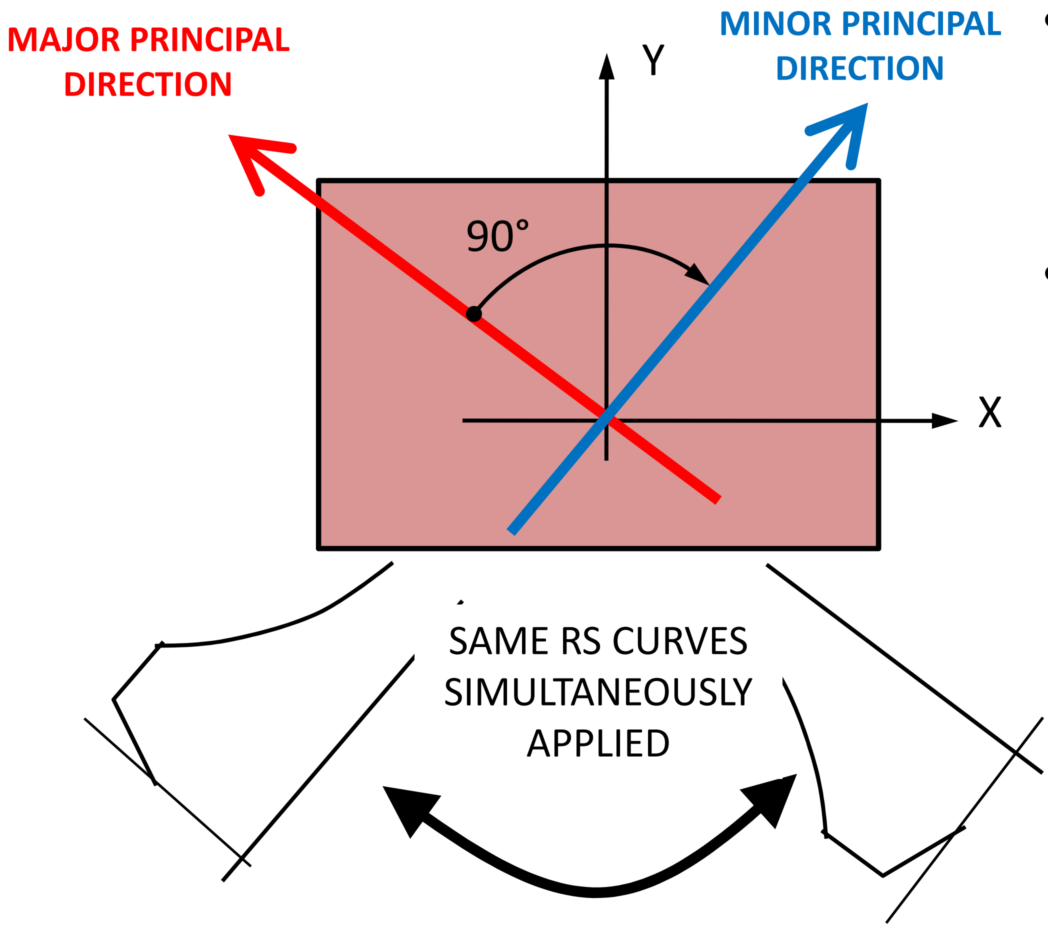
- Principal directions are obvious for regular structures.
- For irregular structures, principal directions are not obvious.

Analysis and Design: Suggestions – Static

- If the structure is regular, follow 100 + 30 rule as usual.
- If the structure is irregular, 100 + 30 may be conservative for max-rotated RS.
  - Depending on the level of irregularities, a RS analysis may be mandated by the code.
  - Engineering judgment. Code, by nature, cannot address all types of irregularities.

Analysis and Design: Suggestions – RS

- FOR GEOMEAN-BASED RS (both regular and irregular):



- **Use**
  - CQC (Modal Comb.)
  - SRSS (Directional Comb.)
- **Scale:**
  - Find base shear for both Major and Minor principal directions.

→ V_{Major} & V_{Minor}

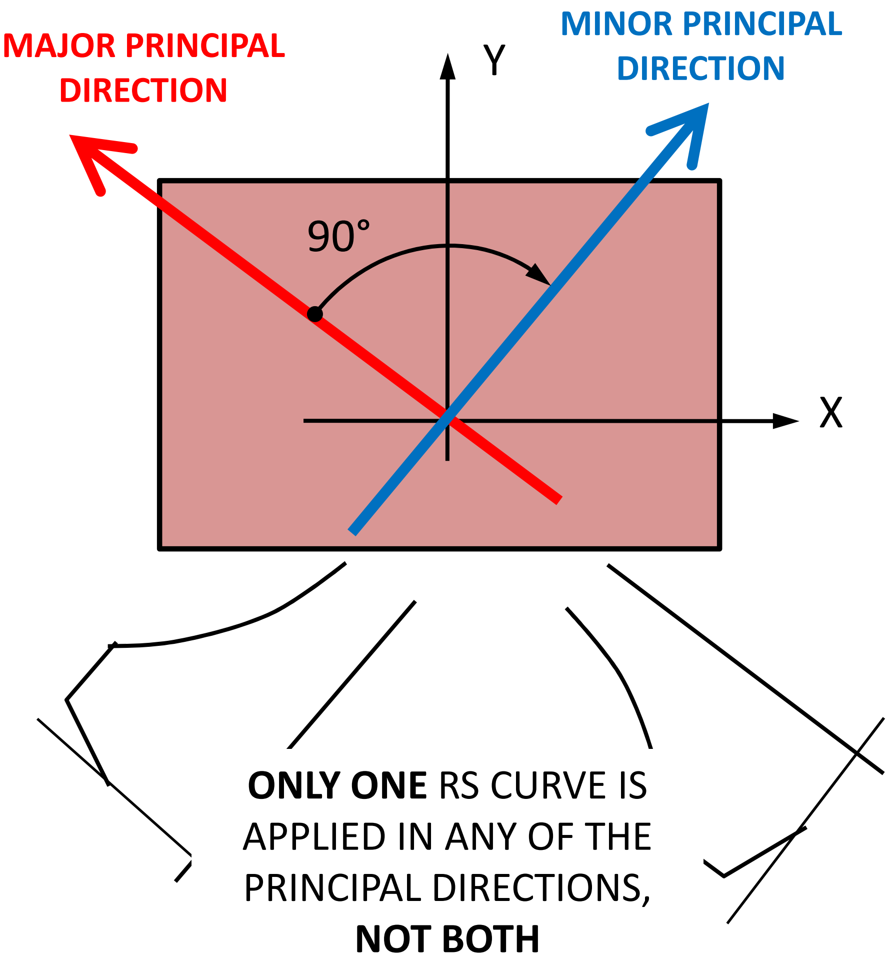
  - Scale both RS curves by the ratio

$$\frac{\text{STATIC BASE SHEAR}}{\text{MIN}(V_{Major}, V_{Minor})}$$

NOTE: ASCE 7 – 05 has a factor or 0.85 in scaling

Analysis and Design: Suggestions

- FOR MAXIMUM-ROTATED RS (For Regular Structures):



- **Use**
  - CQC (Modal Comb.)
- **Scale:**
  - Find base shear for both Major and Minor principal directions.

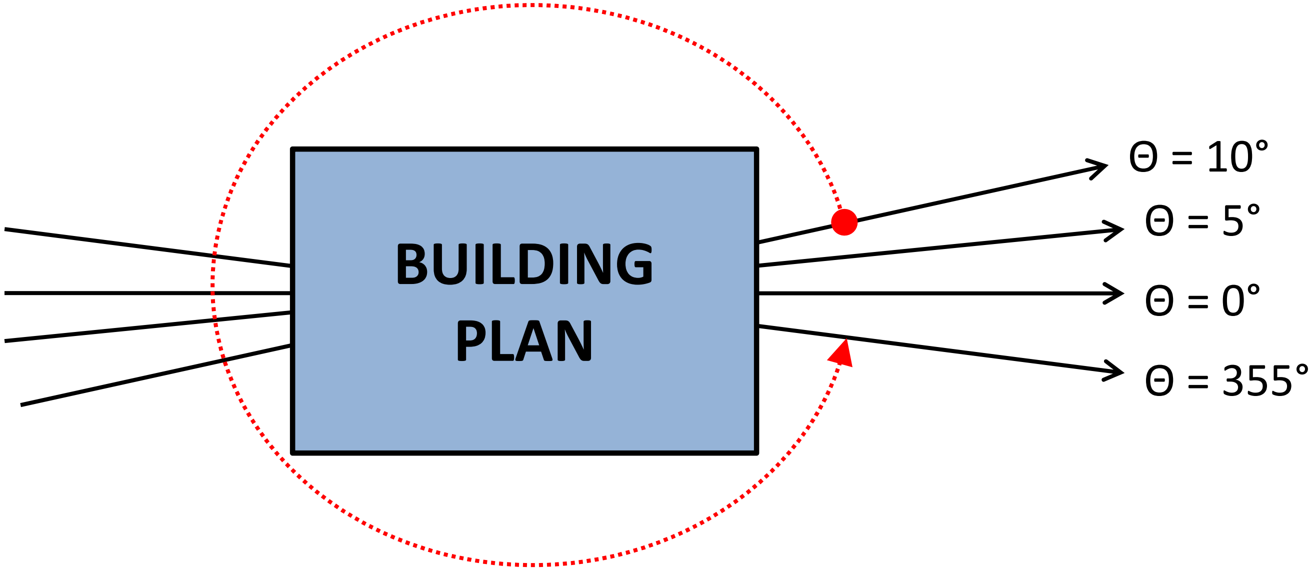
  → V_{Major} & V_{Minor}
  - Scale both RS curves by the ratio

$$\frac{\text{STATIC BASE SHEAR}}{V_{Major} \quad \text{OR} \quad V_{Minor}}$$

NOTE: ASCE 7 – 05 has a factor or 0.85 in scaling

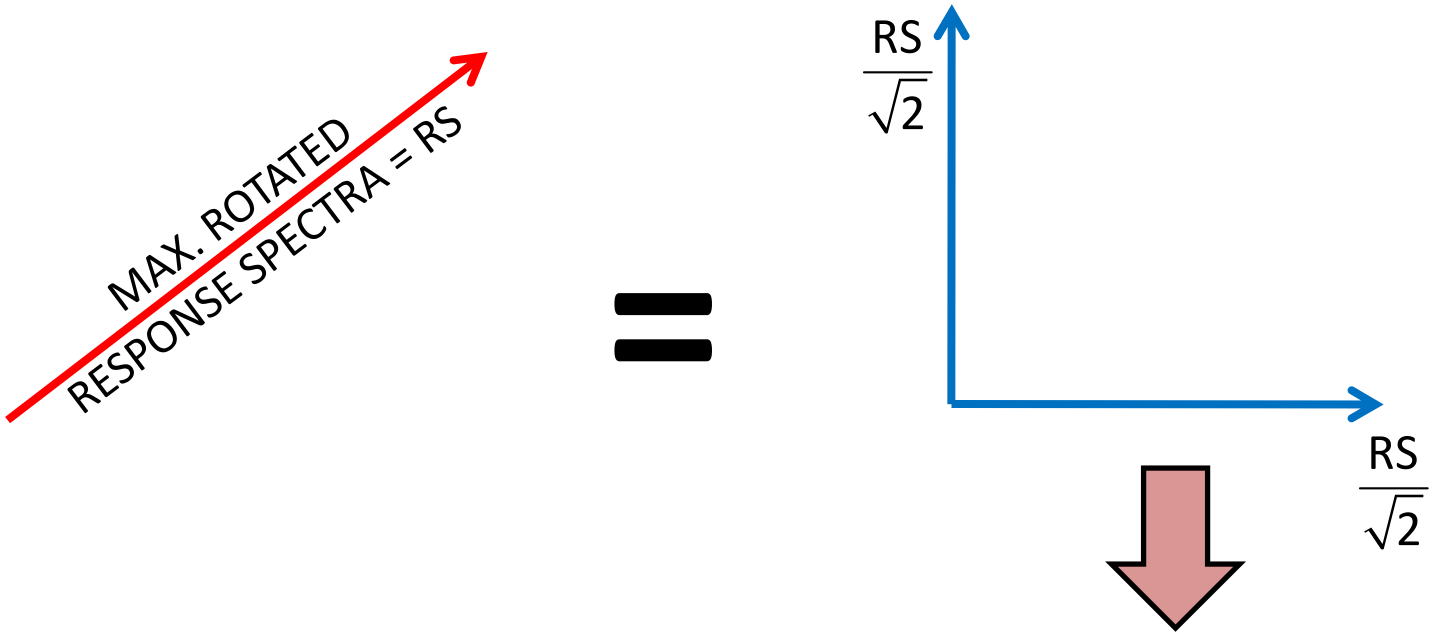
Analysis and Design: Suggestions

- FOR MAXIMUM-ROTATED RS (For Irregular Structures):
  - For irregular structures: Create many load cases for various angles of rotation of structure (NOT RS angle).
  - Scaling is an issue. Perhaps scale to ratio: $\frac{\text{STATIC BASE SHEAR}}{\text{MIN}(V_{\Theta})}$



Analysis and Design: Suggestions

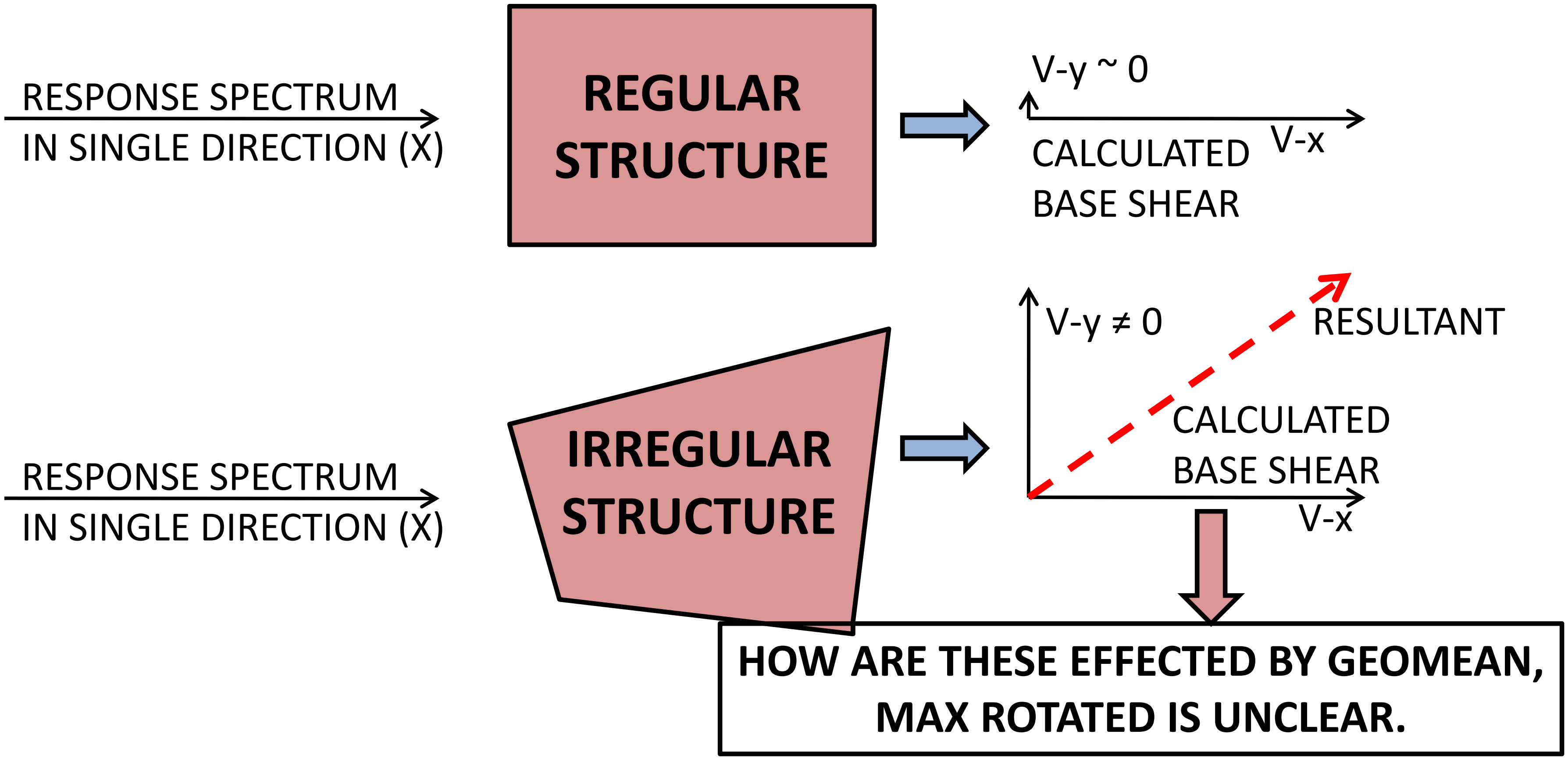
- FOR MAXIMUM-ROTATED RS(For Irregular Str):
  - Alternative Suggestion (requires further study):



THIS FORM OF THE RS IS SUITABLE FOR CQC + SRSS, BUT SCALING SHOULD BE DONE WRT TO MAX ROTATED SPECTRA

Unclear points in Structural Codes

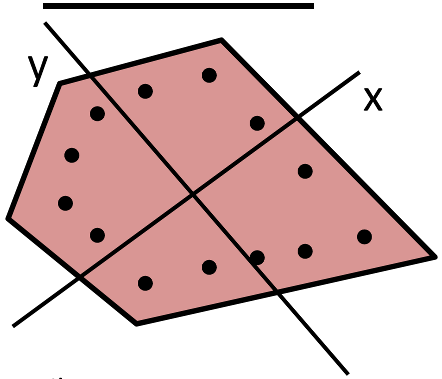
- Many literature agree/emphasize that current structural codes are not clear on some of the procedures and they are left to engineer's judgment.
- Example: Scaling RS base shear to static base shear.

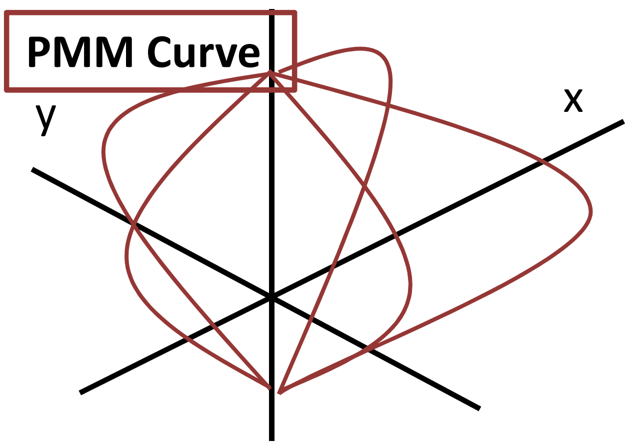


Other Issues: RS analysis, 100 + 30 etc..

- 100 + 30 Procedure
  - May be unconservative for regular structures,.
  - Is almost guaranteed to be unconservative for:
    - Irregular structures, un-orthogonal lateral systems, members have irregular x-sections, and etc…
  - The code cannot address these types of structures as it is too structure specific. Engineer has to make a judgment on the level of accuracy.
- As structure gets complicated, RS analysis, by nature, have limitations → Engineer has to make a judgment

EXAMPLE:

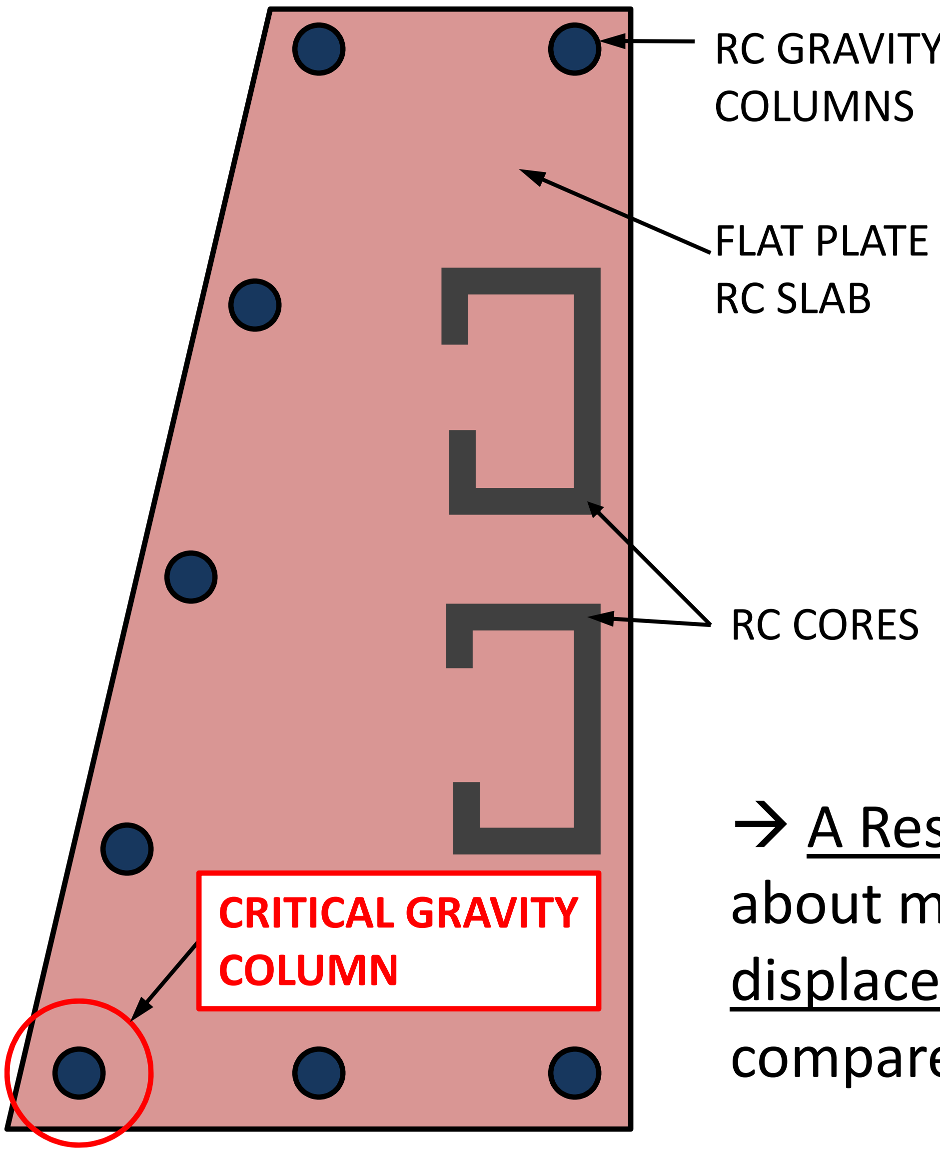




$$\sigma = \frac{P}{A} + \frac{M_x y}{I_x} + \frac{M_y x}{I_y}$$

WHICH LOCAL ANGLE IS MORE CRITICAL?

Case Study:



SUMMARY:

- 11 Story Office Building
- Located in a no-seismicity area
- RC Building
- Extreme torsional irregularity
- Gravity columns are not part of lateral system
- Gravity columns will be highly affected from the lateral loads.

→ A Response Spectrum Analysis resulted about max. 30% larger lateral displacements of gravity columns compared to code defined static analysis.

Conclusions

- There has been significant developments on both **geotechnical** and **structural** aspects of analysis and design for multidirectional seismic motions and orthogonal effects.
- Structural codes are not clear and specific on how recent changes in the RS representations affects structural analysis and design.
- "If you ask 10 different engineers, you will get 10 different answers."
- This is an **"heads-up"** to inform SEs about the procedures and the recent changes; not an attempt to propose new procedure or re-invent the wheel(s).

Conclusions

- The topics on the RS derivation and analysis that are crucial for the estimation of the most critical load affects are explained in a very simple manner from a structural engineer's perspective.
- Simple guidelines are provided to assure the RS analysis yield conservative results based on an extensive literature survey.
- The presenter is very keen to share comments and receive suggestions.
- Baris.Erkus@arup.com

Future Research

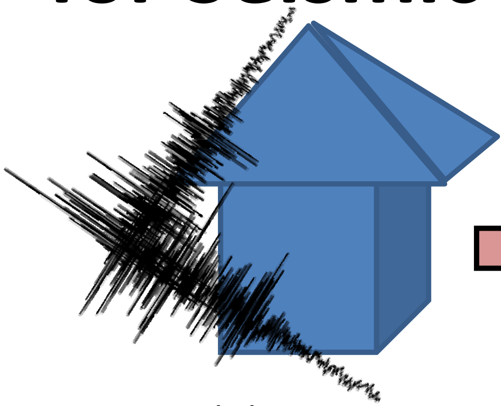
- We are currently evaluating numerically some of these procedures for various types of structures with various levels of irregularities.
- We hope to have an understanding of <u>which method is accurate enough</u> for <u>which type of structure</u>.

CODES? ENGINEERING JUDGMENT? HOW?

SAMITOUR TOWER, CULVER CITY, CA

THANK YOU FOR YOUR ATTENTION

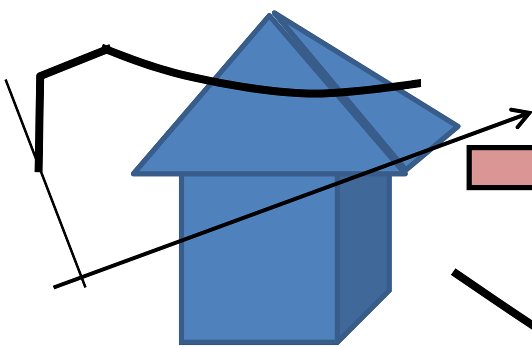
Problem Definition: Analysis and Design for Seismic Events



ONE (1) EQ DATA

TIME-HISTORY ANALYSIS

ACCURATE ESTIMATION OF STRUCTURAL RESPONSES (DISPLACEMENTS, MEMBER FORCES, MEMBER STRESSES) FOR A GIVEN SEISMIC ACCELERATION DATA



RS CURVE REPRESENTS MANY EQ DATA

RESPONSE SPECTRUM ANALYSIS

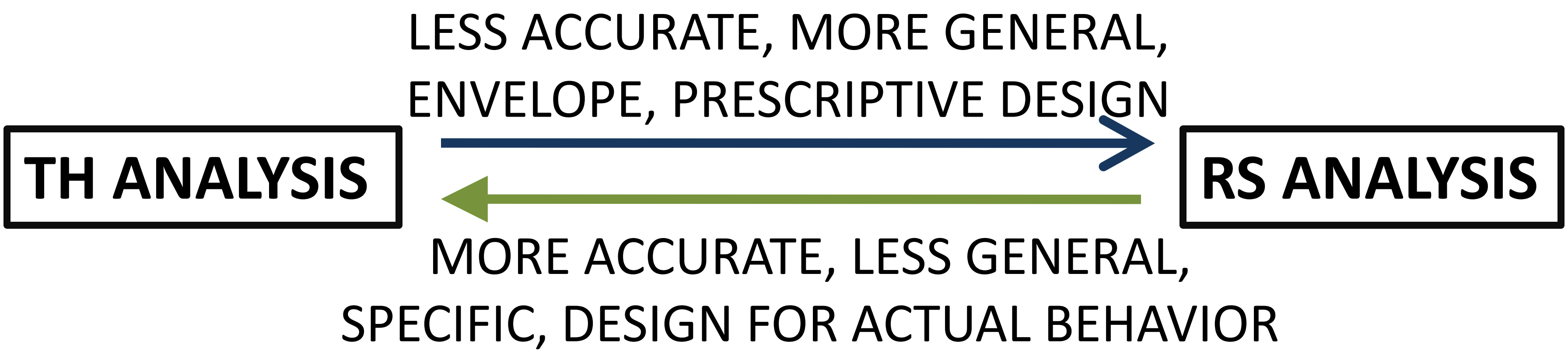
PEAK VALUE OF A **SPECIFIED STRUCTURAL RESPONSE** IS OBTAINED FOR THE GIVEN RS CURVE.

EQUIVALENT LATERAL FORCE PROCEDURE

STATIC ANALYSIS

Modal Combination Procedures

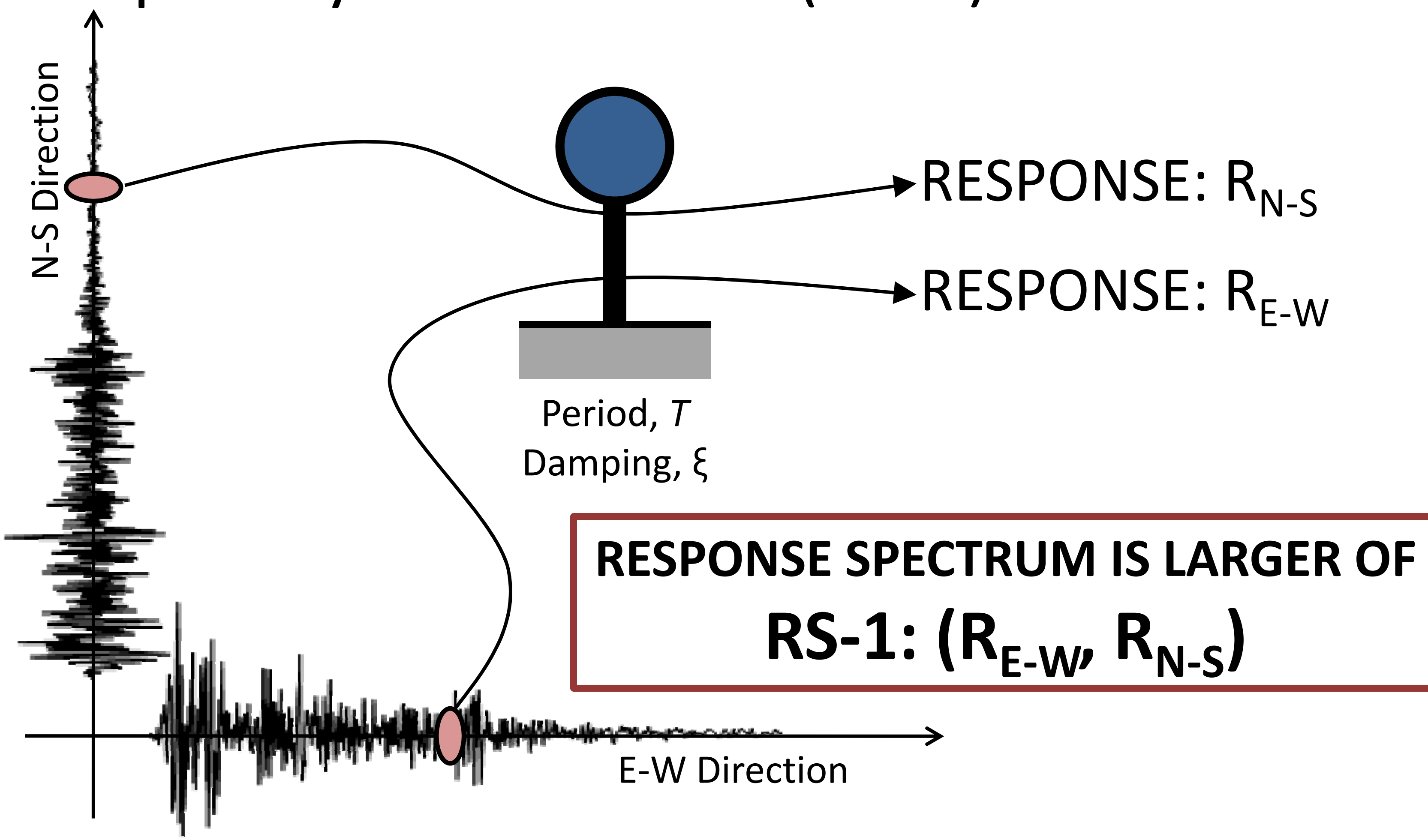
- A Response Spectrum (RS) analysis
  - Is an approximation of a more accurate time-history (TH) analysis.
  - Attempt to address a wider range of seismic events.



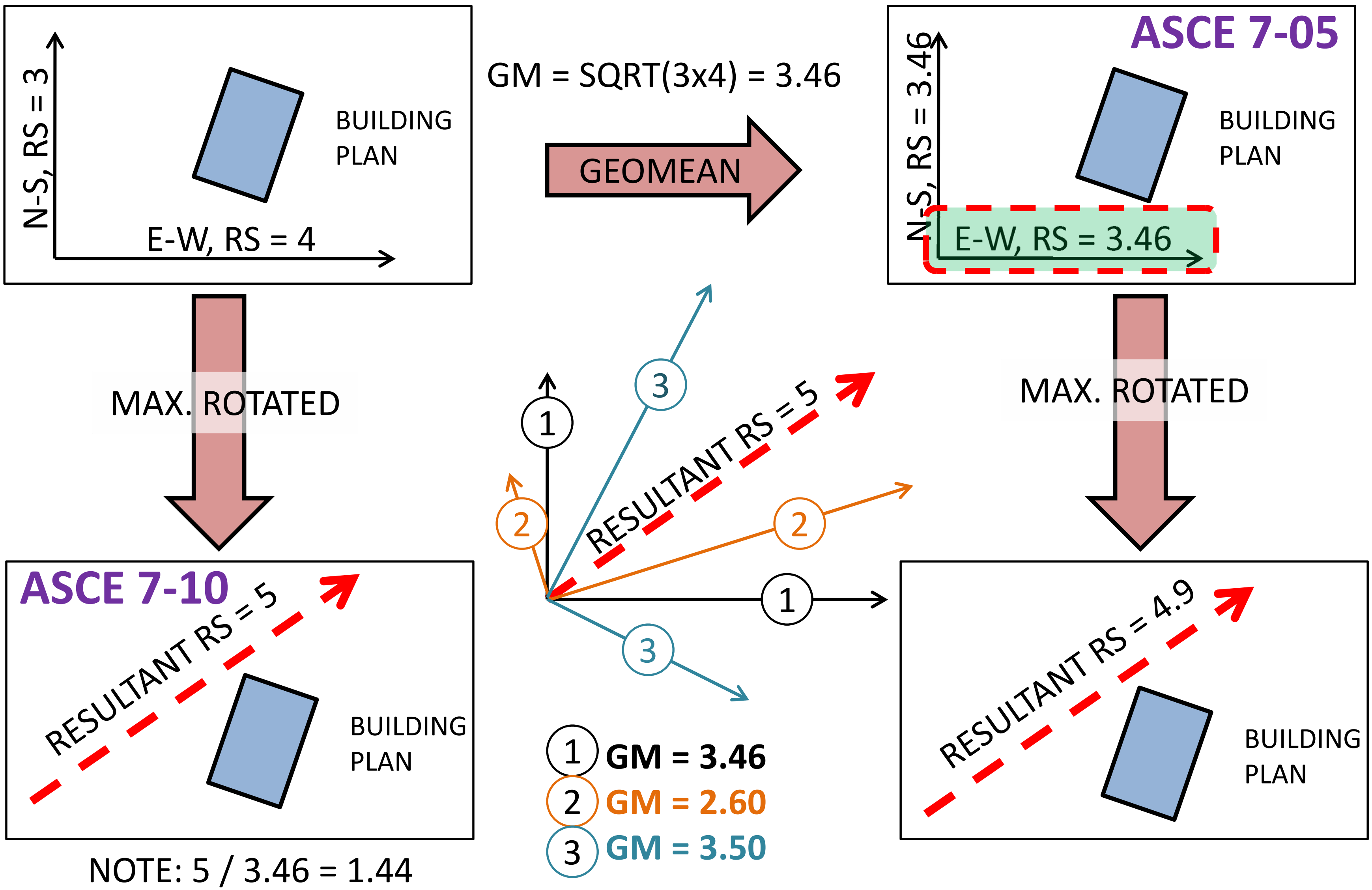
  - Efficiency and applicability of RS analysis is mainly determined by the <u>modal combination</u> and <u>directional combination</u> procedures used.

Response Spectrum Representations

- Larger of the two horizontal components
- Example: Joyner and Boore (1982)

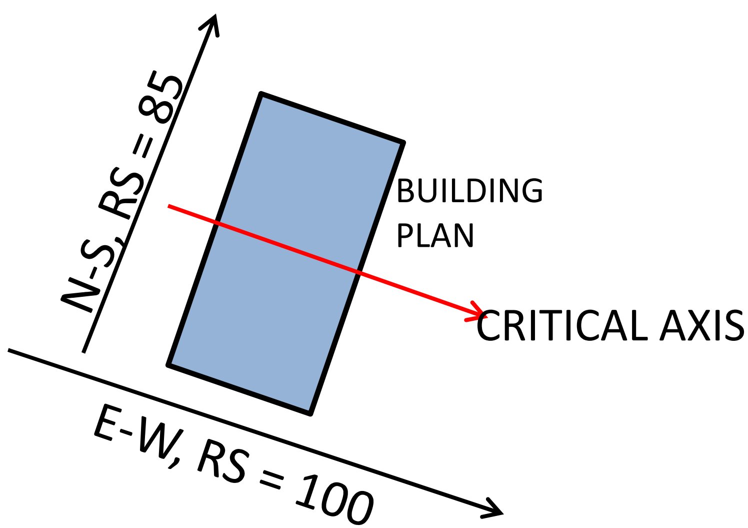


Response Spectrum Representations



Response Spectrum Representations

- Assumptions used in the original development of CQC3 procedure:
- Clough and Penzien (1993), Section 25-3:
  - "… design spectra previously described single component horizontal motion can be used for both components; consistent with the strong ground motion data, the design … intensity levels of one component **should be reduced about 15 percent** below the corresponding intensity level of the other component. The component of larger intensity should be directed along the critical axis of the structure."



- However, many other research shows that this ratio is period dependent and can vary significantly.
- ???

Modal Combination Procedures: CQC

- The following assumptions are implemented in the derivation (Der Kiureghian, 1981):
  - The structure has classical modes
  - Input excitation is a stationary Gaussian excitation
  - The excitation is a wide-band process, i.e., have a smoothly varying power spectral density over a range of frequencies covering the significant modes of vibration of structures
  - In the original derivation, a Kanai-Tajimi filter, with the following parameters is used
    - $\omega_g = 5\pi$, $\zeta_g = 0.6$ (60% damping)
  - There are several other assumptions in the stochastic dynamics portion of the derivation (e.g., peak factors, zero-crossings and etc…)
- Excellent results for most of building type of structures, as long as assumptions are not significantly violated.

Directional Combination Procedures: 100+30

- Clough and Penzien (1993) interpretation of 100%+30% rule: Absolute sum of the responses.
- They compared the results with the multi-component earthquake results with SRSS combination of 100% RS in critical direction and 85% RS in the orthogonal direction. (NOTE: This is questionable. See the previous slides.)
- They conclude that 100% + 30% summation of responses are max. 5% conservative than the SRSS combination.
- They conclude that

  RESPONSE [SRSS(100% RS, 85% RS) ~ **1.12** x RESPONSE [100% RS]
- This interpretation of the 100%+30% procedure seem to be compatible with the <u>Geomean</u> definition of RS.
- Does 100%+30% come from
  - The seismic demand in orthogonal directions
  - Or the structural responses?

Notes:

- The topics discussed in this presentation are considerably complicated and are subject of current research in both seismology and structural engineering. The intention in this presentation is to use a very simple language to communicate this complicated technical information for structural engineering community.
- The information provided herein is mostly a summary and compilation of current literature. The author is keen to receive any feedback on his interpretation of the literature.
- The list of references is currently prepared. Will be available soon.