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The Art of Designing Ductile Concrete in the Past 50 Years: The Impact of the PCA Book and Mete A. Sozen, Part 1

ACI Fall 2012 Convention
October 21 – 24, Toronto, ON

ACI
WEB SESSIONS

Terrence Paret has conducted hundreds of engineering investigations in the U.S. and abroad, focusing on the prediction of structural performance before damaging events, the evaluation of structural performance afterwards, and on the design of repairs and measures to improve behavior. While the majority of his work involves the response of buildings to earthquake ground shaking, his experience encompasses a wide variety of structure types and damaging events, including seismic assessment of the Washington Monument and the United Nations Secretariat, post-collapse analysis of the I-35W Bridge, and post-collapse damage assessment of the MacArthur Maze. For papers related to weld failures observed after the 1994 Northridge earthquake, Mr. Paret was the recipient of the 2001 Moisseiff Award from ASCE. Recently, Mr. Paret managed the seismic strengthening of the State Bar of California Building in San Francisco, which project was awarded the 2008 Presidential Award of Excellence from AISC.

ACI
WEB SESSIONS

A PRESCIENT AXIOM: THE FORMATIVE INFLUENCE OF THE SUBSTITUTE STRUCTURE METHOD

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ACI Convention
Concrete in the Past 50 Years: The Impact of the PCA book and Mete A. Sozen, Part 1 of 2
Sunday, October 21 1:00PM – 3:00PM

A Prescient Axiom: The Formative Influence of the Substitute Structure Method

The transformational role of the Substitute-Structure Method in facilitating the explicit consideration of structure nonlinearity into earthquake engineering analysis and reflection on its progeniture in performance-based seismic assessment and design

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A Prescient Axiom: The Formative Influence of the Substitute Structure Method

- **Prescient**
  - Having foreknowledge or foresight; foreseeing
  - 15th century
  - **Francis Bacon**: "*The providence of King Henry the Seventh was in all men's mouths; who showed himself sensible and almost prescient of this event*"

A Prescient Axiom: The Formative Influence of the Substitute Structure Method

- **Axiom**
  - A proposition that commends itself to general acceptance; a well-established or universally conceded principle; a maxim, rule, law
  - 15th century
  - **Francis Bacon**: "*an empirical law, a generalization from experience*".

Francis Bacon (1561-1626)

Philosopher, statesman, parliamentarian, scientist, jurist and author

- The first modern empiricist
- Developer of the scientific method
- Proponent of inductive method of reasoning
  - o Demonstrating what is so by negation of what is not
  - o Derivation of general axioms from "*particulars*"
- Idealized "Physics" into two branches: Mechanics and Magic

In the beginning…

- 1927 Uniform Building Code (Appendix Chapter 23)
- Base shear coefficient = 7.5% (D+L) when building is on firm soil, 10% otherwise

"The design of buildings for earthquake shocks is a moot question but the following provisions will provide adequate additional strength when applied in the design of buildings or structures" (1927 UBC)

In the beginning…

- 1935 Uniform Building Code (Appendix Chapter 23)
- Base shear coefficient reduced from 7.5% (D+L) to 2% (D+0.5L) when building is on firm soil, and from 10% (D+L) to 4% (D+0.5L), otherwise
- Through 1946 edition

In the beginning…

- 1949 Uniform Building Code (Appendix Chapter 23)
  - o F=CW, C=0.15/(N+4.5)
  - o "C" reduces as the number of stories increased
  - o "C" adjusted by seismic zone, (x4 in California)
  - o 1/3 increase in allowable stress
- Through 1958 edition

In the beginning…

- In 1952, San Francisco ASCE and SEAONC developed a "model lateral force provision" based on dynamics and response spectra
  - o F=CW, C=.15/T
  - o "C" reduced as the number of stories increased
  - o "C" adjusted by seismic zone, (x4 in California)

In the beginning…

- In 1959, SEAOC Seismology Committee published the first Bluebook
- In 1960, SEAOC Seismology Committee published the first "Commentary"
- Their recommendations were adopted into the 1961 UBC
  - o F=ZKCW, C=0.05/ $\sqrt[3]{T}$ (T could be formulaic or analysis based)
  - o Equation accounted for "higher modes"

In the beginning…

- In the 1961 UBC, structural framing systems in buildings more than 13 stories or 160 feet were required to be ductile
- Steel frames with moment-resisting connections were credited automatically with the necessary ductility
- Other systems, however, such as reinforced concrete frames, were required to be "*proven by tests and studies to provide equivalent energy absorption*". (1961 UBC)

In the beginning…

- Thus, the 1961 PCA book "Design of Multi-story Reinforced Concrete Buildings for Earthquake Motions", by Blume, Newmark and Corning (PCA 1961) filled a clear need. The book is a classic and contains much that remains relevant today.

Blume, Newmark and Corning (1961)

- Focuses on the need "*to have an understanding of the manner in which a structure absorbs the energy transmitted to it by an earthquake and the maximum amount of motion or energy the structure can sustain*."

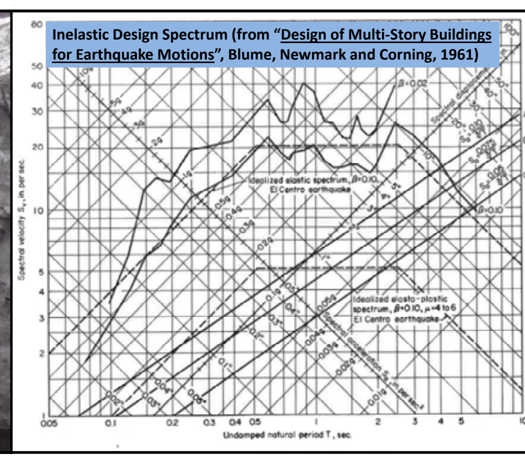
Blume, Newmark and Corning (1961)

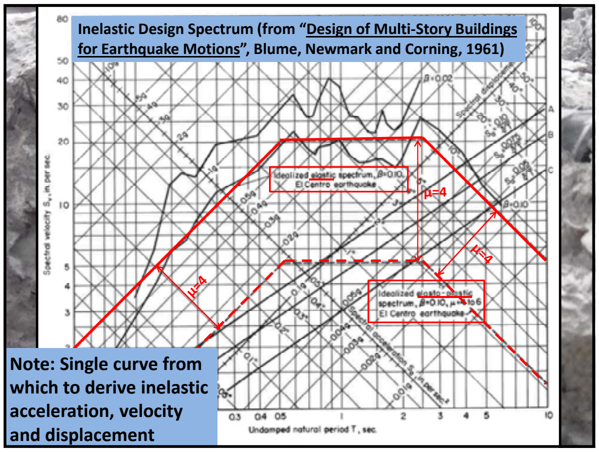
- Response Spectra
- Ductility
- Inelastic response-post yielding
- Inelastic Design Spectra
- Nonlinear pushover
- Reserve Energy Technique

Blume, Newmark and Corning (1961)

- A single page of "conceptual" discussion of inelastic design spectra. Set forth as postulates:
  - Equal displacement ("*spectral displacement of the elasto-plastic system is practically the same as that for an elastic system having the same period of vibration*")
  - Equal energy ("*same for the elasto-plastic system and for the elastic system*")
- "*This energy criterion leads to a slightly different formulation that corresponds also to a shifting down of the spectra by a ratio which, instead of being obtainable by dividing the elastic spectrum by* **μ**, *is obtained by dividing the elastic spectrum by the quantity* $\sqrt{2\mu - 1}$ "
- The single inelastic response spectrum provided in the book reduces the acceleration, velocity and displacement by **μ** across the full range of periods.

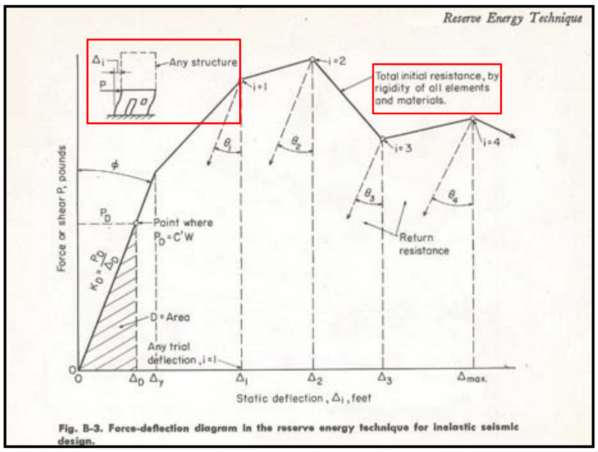
Inelastic Design Spectrum (from "Design of Multi-Story Buildings for Earthquake Motions", Blume, Newmark and Corning, 1961)



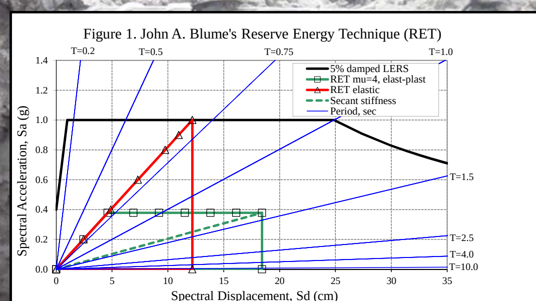


Blume, Newmark and Corning (1961)

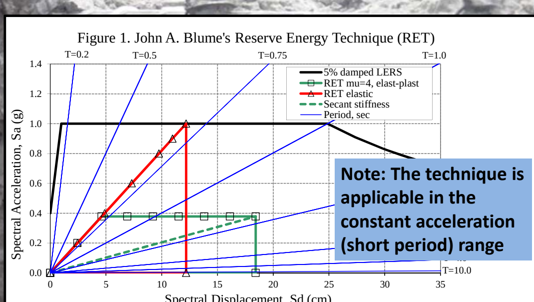
- Reserve Energy Technique
  - o Force-Displacement Analysis (pushover) -
  - "*The force deflection diagram of a structure…can be used graphically or numerically as a measure strain energy and work capacity, as well as a convenient means of adjusting the period, estimating the permanent yield or damage, and of visualizing the basic problem*."



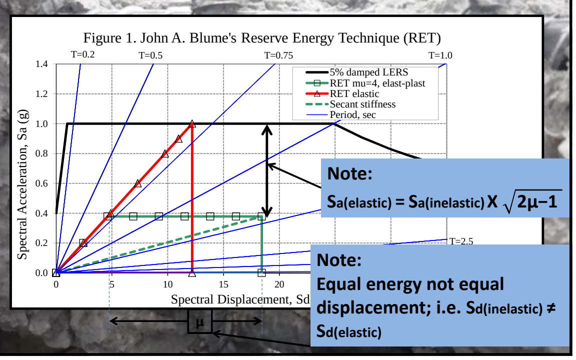
John A. Blume's Reserve Energy Technique (1961)

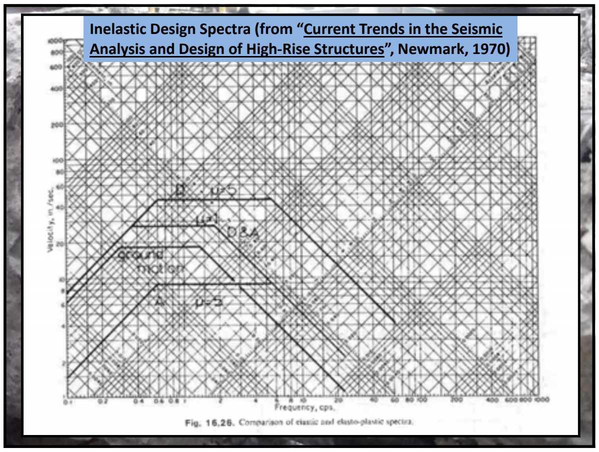


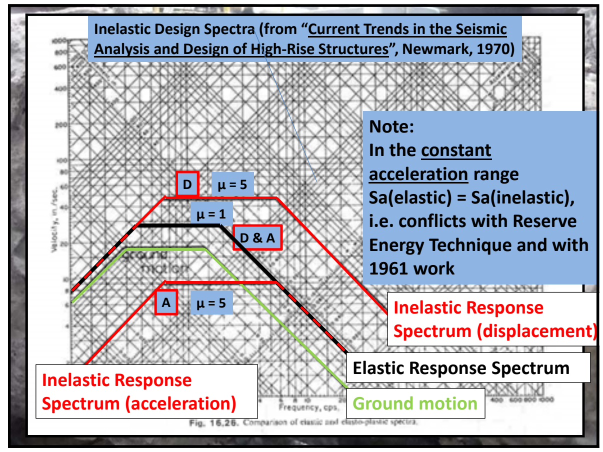
John A. Blume's Reserve Energy Technique (1961)

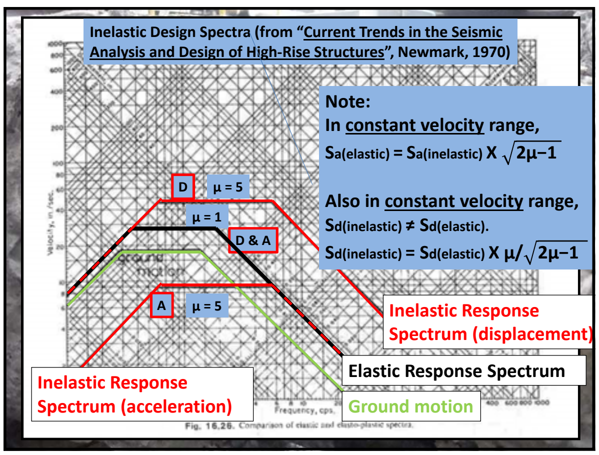


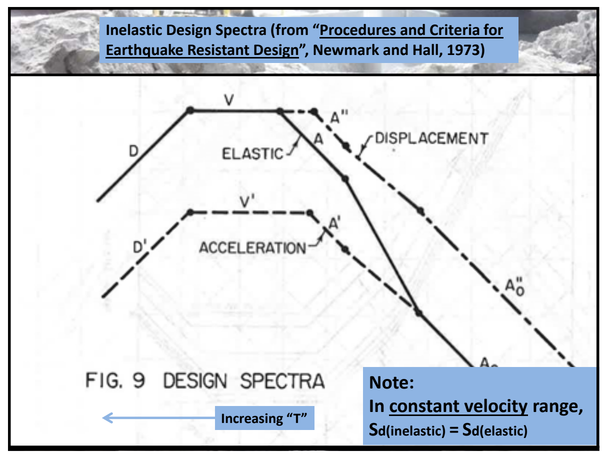
John A. Blume's Reserve Energy Technique (1961)

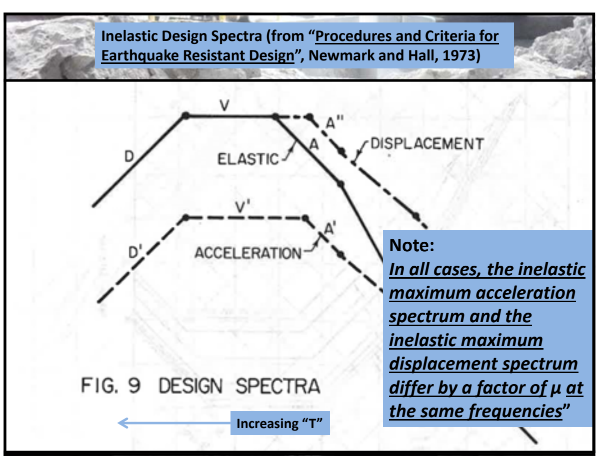


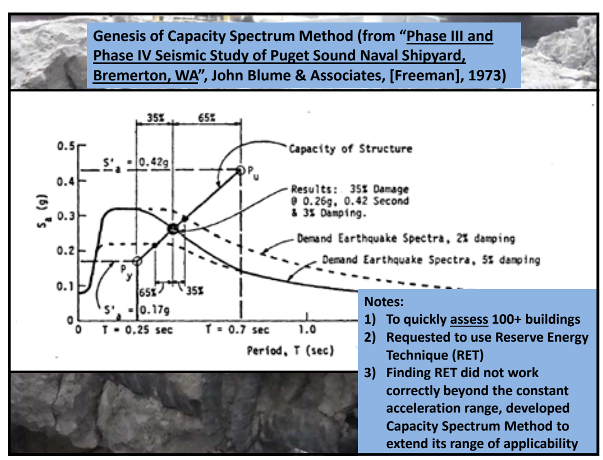

Inelastic Design Spectra (from "Current Trends in the Seismic Analysis and Design of High-Rise Structures", Newmark, 1970)
D μ=5
μ=1
D&A
ground motion
A μ=5
Frequency, cps
Fig. 16.26. Comparison of elastic and elasto-plastic spectra.


Inelastic Design Spectra (from "Current Trends in the Seismic Analysis and Design of High-Rise Structures", Newmark, 1970)
Note:
In the constant acceleration range Sa(elastic) = Sa(inelastic), i.e. conflicts with Reserve Energy Technique and with 1961 work
D
μ = 5
μ = 1
D & A
A
μ = 5
Inelastic Response Spectrum (displacement)
Elastic Response Spectrum
Inelastic Response Spectrum (acceleration)
Ground motion
Fig. 16.26. Comparison of elastic and elasto-plastic spectra.

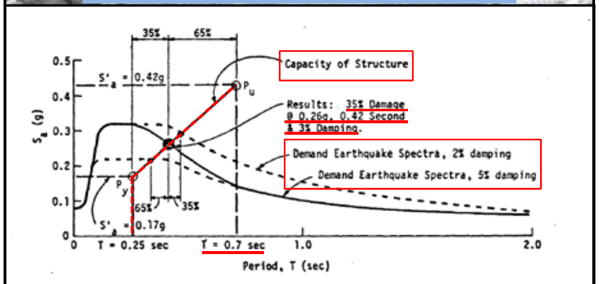

Inelastic Design Spectra (from "Current Trends in the Seismic Analysis and Design of High-Rise Structures", Newmark, 1970)
Note:
In constant velocity range,
Sa(elastic) = Sa(inelastic) X √2μ−1
Also in constant velocity range,
Sd(inelastic) ≠ Sd(elastic).
Sd(inelastic) = Sd(elastic) X μ/√2μ−1
D
μ = 5
μ = 1
D & A
A
μ = 5
Inelastic Response Spectrum (displacement)
Elastic Response Spectrum
Inelastic Response Spectrum (acceleration)
Ground motion
Fig. 16.26. Comparison of elastic and elasto-plastic spectra.


Inelastic Design Spectra (from "Procedures and Criteria for Earthquake Resistant Design", Newmark and Hall, 1973)
V
A"
D
ELASTIC
A
DISPLACEMENT
V'
D'
A'
ACCELERATION
A"0
FIG. 9 DESIGN SPECTRA
Increasing "T"
Note:
In constant velocity range,
Sd(inelastic) = Sd(elastic)


Inelastic Design Spectra (from "Procedures and Criteria for Earthquake Resistant Design", Newmark and Hall, 1973)
V
A"
D
ELASTIC
A
DISPLACEMENT
V'
D'
A'
ACCELERATION
FIG. 9 DESIGN SPECTRA
Increasing "T"
Note:
In all cases, the inelastic maximum acceleration spectrum and the inelastic maximum displacement spectrum differ by a factor of μ at the same frequencies"

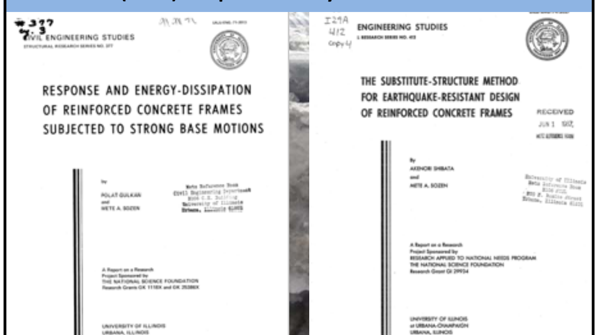

Genesis of Capacity Spectrum Method (from "Phase III and Phase IV Seismic Study of Puget Sound Naval Shipyard, Bremerton, WA", John Blume & Associates, [Freeman], 1973)
35%
65%
Capacity of Structure
S'a = 0.42g
Pu
Results: 35% Damage @ 0.26g, 0.42 Second & 3% Damping.
Demand Earthquake Spectra, 2% damping
Demand Earthquake Spectra, 5% damping
Sa (g)
Py
65%
35%
S'y = 0.17g
T = 0.25 sec
T = 0.7 sec
1.0
Period, T (sec)
Notes:
1) To quickly assess 100+ buildings
2) Requested to use Reserve Energy Technique (RET)
3) Finding RET did not work correctly beyond the constant acceleration range, developed Capacity Spectrum Method to extend its range of applicability

Genesis of Capacity Spectrum Method (from "<u>Phase III and Phase IV Seismic Study of Puget Sound Naval Shipyard, Bremerton, WA</u>", John Blume & Associates, [Freeman], 1973)



- **Structural Analysis Environment**
  - Wilson, E. L, "**<u>SAP – A General Structural Analysis Program</u>**", SESM Report 70-20, Dept. of Civil Engineering, University of California, Berkeley, California, 1970
  - Wilson, E. L. and Dovey, H. H., "**<u>Three Dimensional Analysis of Building Systems – TABS</u>**," EERC, Report No. 72-8, University of California, Berkeley, California, December 1972
  - Bathe, K., Wilson, E., and Peterson, F., "**<u>SAP IV A Structural Analysis Program for Static and Dynamic Response of Linear Systems</u>**," EERC, Report No. 73-11, University of California, Berkeley, California, June 1973

- **The Substitute-Damping (1971) and Substitute-Structure Methods (1974) are published by the Univ. of Illinois**



- **And later by the ACI Journal (1974) and the ASCE Journal of Structural Engineering (1976), respectively**

- **Prior to the Substitute-Structure Method:**
  - Design methods are force-based and begin with calculation of design forces based on elastic period
  - No substantive consideration of displacement, element distortions, or damage ("Lateral…drift…shall be considered in accordance with accepted engineering practice")
  - No weighting of the intended function of structure as a factor in tolerable performance
  - No explicit recognition of element "degradation" except via "K" factor
  - No design methodology leveraging the potential advantages of computer-aided design
  - Substantial study of the behavior of R/C frames in the lab and study to develop expressions to describe the behavior of yielding systems, but little to merge the two

- **The Substitute-Structure Method was seminal, revolutionary and transformative**
  - It discarded the idea that seismic design ought to commence with the determination of design forces (in recognition that earthquake damage correlates better with displacement/deformation than with strength)
  - <u>It touted the importance of first identifying the quantum of damage that is tolerable as the key metric in design (i.e. PBE)</u>
  - It was, fundamentally, the first displacement-based design method --- 20 years ahead of its time

- **The Substitute-Structure Method was seminal, revolutionary and transformative**
  - It diminished the significance of the elastic period in the development of a structural/seismic design
  - It explicitly accounted for an intended level of inelastic behavior of the elements in the structure and the structural system as a whole is the design process
  - It explicitly identified the intended function of the structure being designed as a key factor in the development of the design criteria
  - It anticipated the coming of computerized application of elastic methods as a tool in design.

- **Testament to The Substitute-Structure Method being seminal, revolutionary and transformative is that today, it appears to be wholly ordinary**
- **Its underlying premises have been absorbed into and pervade modern earthquake engineering theory, practice and methodology**

The Substitute-Structure Method (from "<u>The Substitute-Structure Method for Earthquake-Resistant Design of Reinforced Concrete Frames</u>", Shibata and Sozen, 1974)

- "…a procedure for determining design forces…for a reinforced concrete structure…"
- "…its objective is to establish the minimum strengths the components of a structure must have so that a tolerable response displacement is not likely to be exceeded."
- "…a simple vehicle for taking account of inelastic response in the design of multi-degree-of-freedom structures."
- "…use of linear elastic models…"
- "…deliberate consideration of displacement in the design process…"

Main Characteristics of the Substitute Structure Method

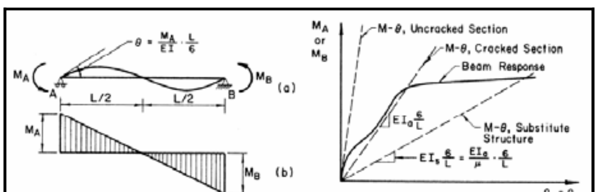
- Definition of a substitute frame whose stiffness is related to but different from the actual frame in the elastic range (In order to account for inelastic response)
- Calculation of design forces from a response spectrum analysis of the substitute frame (For ease of application…)

Main Characteristics of the Substitute Structure Method

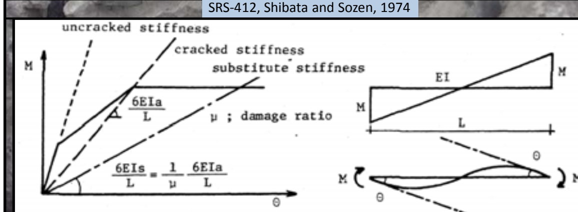
- Equivalence is obtained by incorporating element-by-element modifications to mathematical models of undamaged element models, thus accounting for:
  - the reduced "effective" stiffness of damaged elements
  - energy dissipation
  - ductility
  - changes in modal damping ratios

Primary Steps in the Substitute-Structure Method

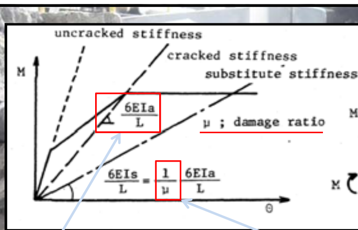
- Determine stiffness of substitute frame members *based on pre-determined <u>tolerable</u> limits of inelastic response* (in contrast to Substitute-Damping Method)
- Calculate *effective* (substitute) stiffness of members
- Calculate *equivalent* (substitute) damping for members
- Modal analysis based on characteristics of the substitute frame (accommodates MDOF)
- Determine design forces from RSA
- (Iterate on "ductility" to ensure capacity > demand)



SRS-412, Shibata and Sozen, 1974



ASCE Journal of the Structural Division, Shibata and Sozen, 1976



Substitute structure stiffness is calculated *as a fraction of the fully-cracked section stiffness* when the member ends reach yield.

Substitute structure stiffness is calculated as a function of the tolerable damage ratio, (secant stiffness at tolerable deformation limit).

Substitute equivalent viscous damping factor (element), β = (f)μ
Substitute damping factor (structure) = weighted average in proportion to its relative strain energy

The Legacy

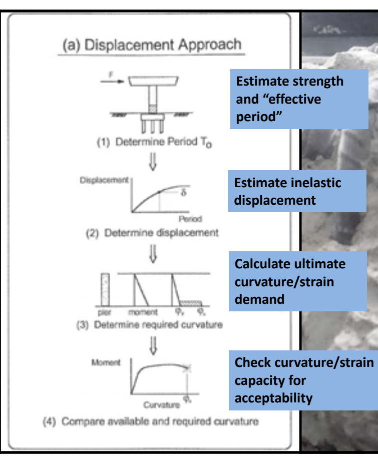
- Performance-based engineering methods which set forth pre-selection of desired performance related to acceptable levels of damage (ATC-40, FEMA 273, FEMA 356, ASCE-41…)

The Legacy

- Displacement-based design methods in which deformation-based metrics are used to directly judge the acceptability of an existing or proposed design
- Displacement-based methods in which deformation-based metrics are used to directly arrive at design decisions

Substitute-Structure "Progeny"

- **"Displacement-Based Design of RC Structures Subjected to Earthquakes", Moehle 1992**
  - proposes that drift should be a focal point of the design process, not just considered indirectly via ductility
  - emphasizes the importance of distribution of drift over the height, implicitly, the local concentration of inelastic behavior.
  - emphasizes effects of drift on nonstructural and non-lateral load resisting elements.
  - promotes practicality of calculation by "attributing" all displacement to inelastic action
  - points out that force-based D/C ratios (IDRs) are ill-suited for quantifying local concentrations of ductility demand, and the need to retain consideration of force and ductility in displacement-based approaches



Substitute-Structure "Progeny"

- **Direct Displacement-Based Design, Priestley 1993**
  - The essence of the method, which is directly attributable to Substitute-Structure, is to characterize the effective (secant) stiffness and the level of equivalent damping at the maximum design displacement, based on limiting member
  - Substitute-structure is defined assuming an inelastic first-mode shape and defining the displacement of the critical member
  - Employs SDOF representation of that system at peak response, determined by "equal work"
  - Objective is to achieve a given performance limit state under a given seismic intensity

Substitute-Structure "Progeny"

- **Secant Method, Kariotis, et al, 1994**

  An iterative method involving :
  - analysis of the structure using an assumed stiffness
  - computation of the displacement demand and resulting stiffness reduction via the secant
  - revision of the input parameters and re-analyzing until convergence
  - Does not employ any increase in damping
  - Adopted into Division 95 of City of LA Building Code for non-ductile concrete buildings

Substitute-Structure "Progeny"

- **"Direct Displacement Based Design of RC Bridge Columns", Kowalsky et al 1994**
  - Updates Priestley's DDBD
  - Rather than estimating peak displacement, a limit on displacement is imposed in order to determine the required properties of the system

Substitute-Structure "Progeny"

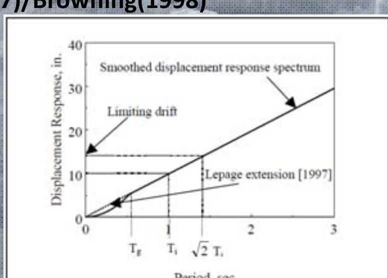
- **Displacement Coefficient Method, ATC-40 (1996)**
  - Employs secant stiffness as a basis for calculation of an effective period and a spectral acceleration
  - Relies on numerous coefficients to arrive at a "target displacement" for the "yielding" structure, based on the spectral acceleration
  - Coefficients "convert" spectral displacement to roof displacement and maximum inelastic displacements to elastic displacement
  - Coefficients account for effect of hysteresis shape and second order effects
  - Employs a bilinear capacity curve to compare with target displacement

Substitute-Structure "Progeny"

- **Target Period Method, LePage (1997)/Browning(1998)**
  - Design method for proportioning based on simplified displacement response spectrum and drift-based performance criteria
  - Selection of target period at maximum tolerable "average" drift
  - Proportion members and iterate to achieve target period
  - Upper bound on displacement is defined from a simplified response spectrum using a period elongation of $T\sqrt{2}$

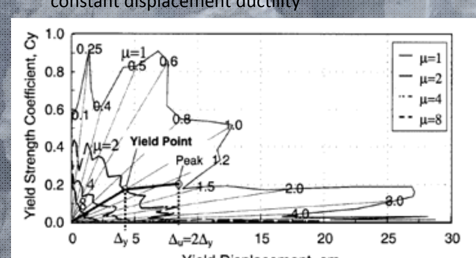
Substitute-Structure "Progeny"

- **Target Period Method, LePage (1997)/Browning(1998)**



Substitute-Structure "Progeny"

- **Yield Point Spectra, Aschheim, 1999**
  - Plots spectra based on yield point for systems having constant displacement ductility



Substitute-Structure "Progeny"

- **Yield Point Spectra, Aschheim, 1999**
  - Utilizes SDOF to construct YPS
  - Superposes a pushover curve to identify yield point displacement ductility for a system, and therefore a peak inelastic displacement
  - Estimates displacement demands while allowing for determination of admissible combinations of strength and stiffness to satisfy performance-based design objectives
  - Variant of Capacity Spectrum Method but employs Substitute Structure perspective re: displacement-based delimiters to meet performance objectives

Substitute-Structure "Progeny"

- **Caltrans Seismic Design Criteria (1999)**
  - Compares displacement demands to displacement capacity
  - Generates demands using elastic response spectrum analysis assuming equal displacement rule
  - Determines displacement capacity via pushover analysis
  - Requires that displacement demand exceeds displacement capacity
  - Design for shear based on capacity design

Closing

- The lineage of much of the approach and philosophy of earthquake engineering today --- even at the leading edge today --- can be traced back to the work and influence of Mete Sozen, as exemplified by the Substitute Damping and Substitute Structure Methods in the early 1970's
- The prerequisite to performance-based assessment and design, and to displacement-based design, is the pre-selection of acceptable performance objectives – which was the underlying premise of the Substitute-Structure Method
- Sozen has long stressed that deformation-based metrics, not strength, ought to define the primary seismic design criteria for securing desirable seismic response, despite strength being used as such for decades. This is now taken for granted throughout the earthquake engineering industry.