# *PAST, PRESENT AND FUTURE*

# *OF*

# *EARTHQUAKE ANALYSIS OF STRUCTURES*

***By Ed Wilson***

***September 22, 2014***

***SEAONC Lecture # 1***

# *Summary of Lecture Topics*

*General Comments*

*Fundamental Principles of Mechanics and Nature*

*Methods of Dynamic Analysis and new Numerical Methods*

*Existing Problems with the Response Spectrum Method, RSM*

*Speed of Computers and New Numerical Methods*

*History of the SAP Series of Programs*

*Damping and Energy Dissipation*

*Recommendations on the RSM, by Ed and Others*

# *The Life Story of Ed Wilson*

*Born in 1931 near Ferndale, CA –* ***The Earthquake Capital of USA***
*Worked on a small ranch and in construction with my father*
*Moved to Sacramento in 1948 - After community college transferred to CAL for BS Degree in January 1955. 53-54 worked as Field Eng.*

*1955 – 56 Korea in the US Army*

***1957 – 63 Worked with Ray Clough for MS and D Eng***

*1963 – 65 Senior Research Engineer Aerojet - on the Apollo Project*

*1965 – 91 Teaching, Consulting and Research at CAL – 29 Docs*

***1981 – Started the development of SAP 80 for Personal Computers***

*1991 – Consulting and Computer Program Development* ***SADSAP***

*Present ECRB 29 years CalTrans SAB 5 years* ***Campus SRC***

# *Professor Ray W. Clough*

*1938  First to Climb Several Cascade Mountains*

*1942  BS University of Washington, Civil Eng.*

*1943 - 1946  U. S. Army Air Force*

*1946 - 1949  MIT - D. Science  - Bisplinghoff*

*1949 - 1986  Professor of CE  U.C Berkeley*

*1952 and 1953  Summer Work at Boeing*

*National Academy of Engineering  & Science*

*National Medal of Science*

To Ray Clough
Best Wishes

# *Fundamental Equations of Structural Analysis*

1. ***Equilibrium*** *- Including Inertia Forces* - ***Must be Satisfied***
2. ***Material Properties*** *or Stress / Strain or Force / Deformation*
3. ***Displacement Compatibility*** *Or Equations or Geometry*

# *Methods of Analysis*

1. ***Force – Good for approximate hand methods***
2. ***Displacement - 99 % of programs use this method***
3. ***Mixed*** **-** *Beam* **-** *Plane Sections & V = dM/dz*

# *Check Conservation of Energy*

# *1964 Gene's Comment – a true story*

- *Ed developed a new program for the Analysis of Complex Rockets*

*Ed talks to Gene ------*

*Two weeks later Gene calls Ed ------*

*Ed goes to see Gene -----*

*The next day, Gene calls Ed and tells him*

***"Ed, why did you not tell me about this program.***

***It is the greatest program I ever used."***

# *Methods for the Earthquake Analysis of Linear Structures*

***Mode  Superposition***  -    *With Model Damping*

***Step-By-Step Integration***    - *No Mode Shapes Needed*

*With Rayleigh Damping and other Possible Numerical Problems*

***Frequency Domain*** – *Maybe good for Certain Problems*

***Approximate  Response  Spectrum*** – *OK  for one degree of freedom*

# *Methods for the Earthquake Analysis of Non-Linear Structures*

***<u>Step-By-Step Integration</u>*** *- No Mode Shapes Needed*

*With Rayleigh Damping and other Possible Numerical Problems*

*a. New Stiffness Matrix formed for each time step and iterate*

*b. In General, the high frequencies have large numerical damping.*

***<u>Fast Non-Linear Analysis Method</u>*** *FNA Method and*

***<u>Using Load Dependent Ritz Vectors</u>*** *LDR Vectors*

*Over 20 years of very positive experience with very large structures*

*Speed, Accuracy, Error Evaluation and Conservation of Energy*

# My First Earthquake Engineering Paper
# October 1-5 1962

SYMPOSIUM

ON THE USE OF

**computers in civil engineering**

OCTOBER 1-5 1962

LNEC

Laboratorio Nacional de Engenharia Civil    Lisbon - Portugal

PAPER Nº.45

DYNAMIC RESPONSE BY STEP-BY-STEP MATRIX ANALYSIS

by

Edward L. Wilson[1] and Ray W. Clough[2]

# ***THE PRESENT***

***Comments on the***

***Response Spectrum Analysis Method***

***SEISMIC DESIGN CRITERIA***

***As used by***

***Many Large Engineering Groups***

# *Topics*

1. *Why do most Engineers have Trouble with Dynamics?*

   *Taught by people who love math – No physical examples*

2 *Who invented the Response Spectrum Method?*

   *Ray Clough and I did – by putting it into my computer program*

3 *Application to "Ordinary Standard Structures"*

   *Why 30 ? Why reference to Transverse & Longitudinal directions?*

4 *Physical behavior of Skew Bridges – Failure Mode*

5 *Why use the 1960 Equal Displacement Rule?*

6 *Quote from George W. Housner*

# *Who Developed the <u>Approximate</u> Response Spectrum Method of Seismic Analysis of Bridges and other Structures?*

*1. Fifty years ago there were only digital acceleration records for 3 earthquakes.*

*2. Building codes gave design spectra for one degree of freedom systems with no guidance of how to combine the response of the higher modes.*

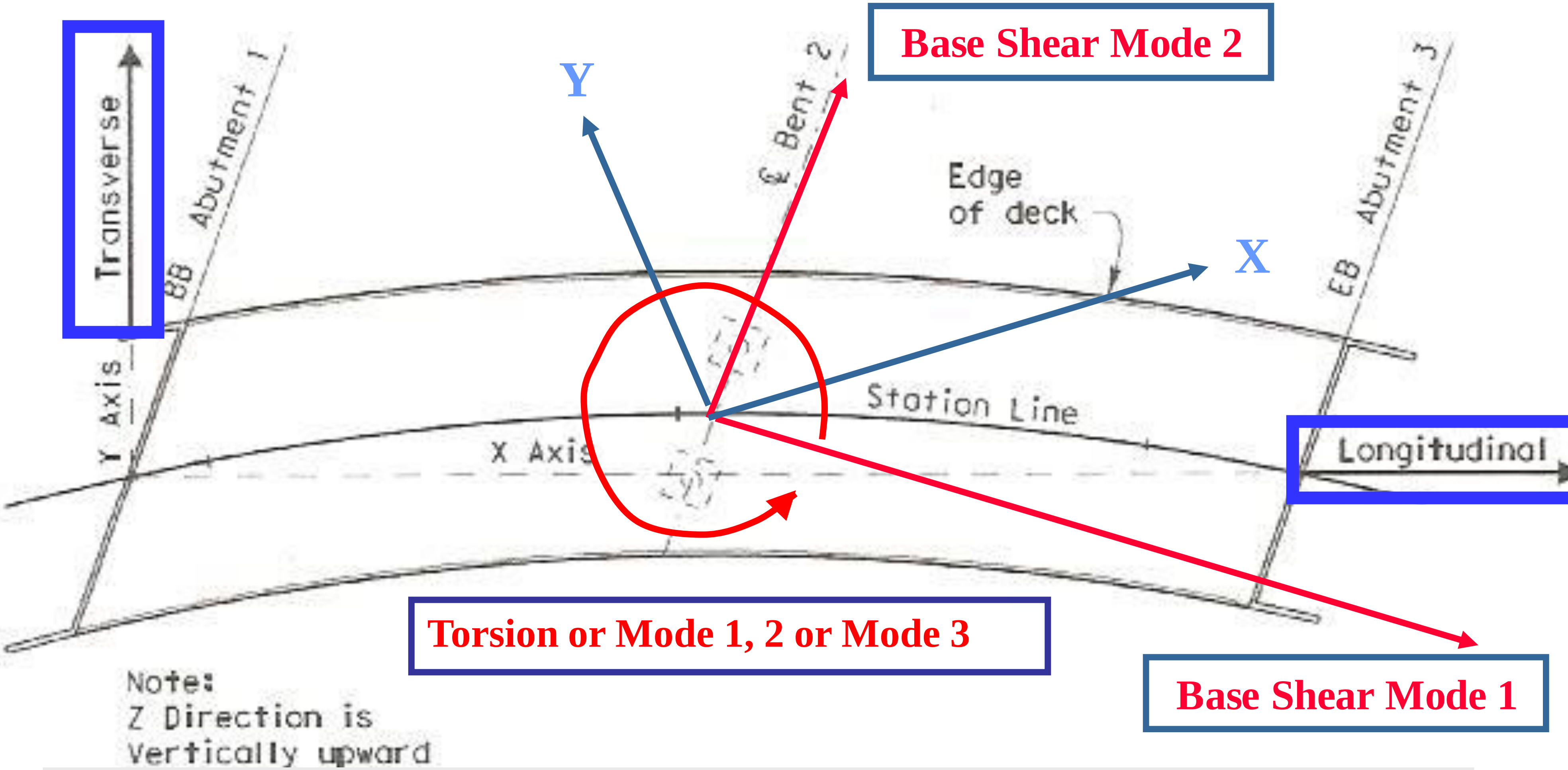
*3. At the suggestion of Ray Clough, I programmed the square root of the sum of the square of the modal values for displacements and member forces. However, I required the user to manually combine the results from the two orthogonal spectra. Users demanded that I modify my programs to automatically combine the two directions. I refused because there was no theoretical justification.*

*4. The user then modified my programs by using the 100%+30% or 100%+40% rules.*

*5. Starting in 1981 Der Kiureghian and I published papers showing that the CQC method should be used for combining modal responses for each spectrum and the two orthogonal spectra be combined by the SRSS method.*

*6. We now have Thousands or of 3D earthquake records from hundreds of seismic events. Therefore, why not use Linear or Nonlinear Time-History Analyses that SATISFIES FORCE EQUILIBRIUM at every point in time.*

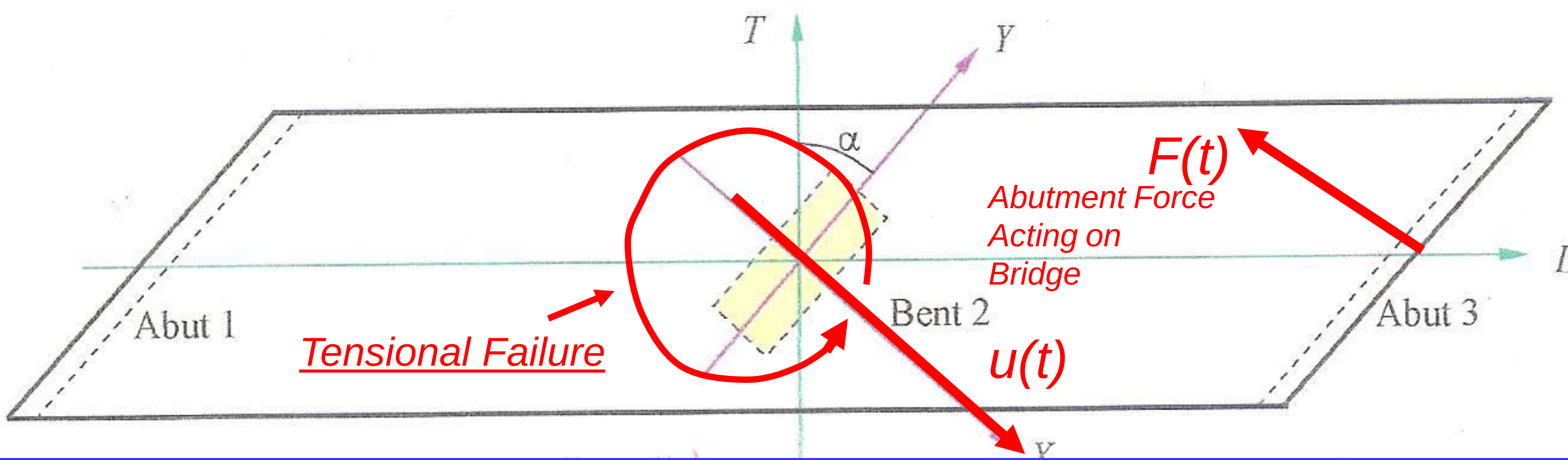
# *If Equal Spectra are applied to any Global X–Y-Z System*



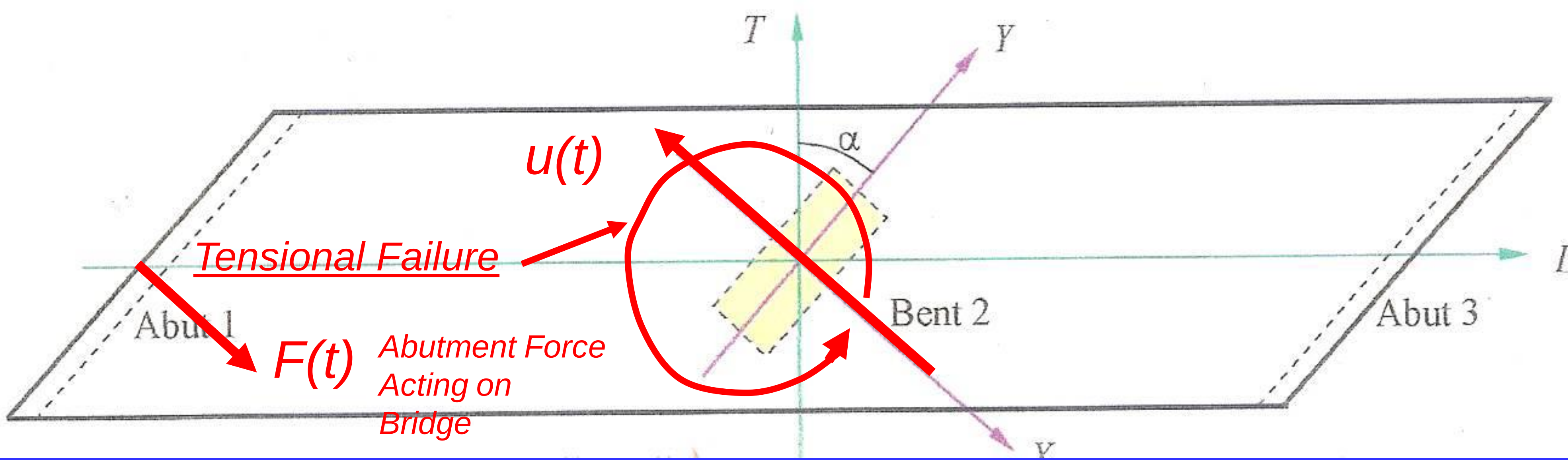

***Member Forces are the same for all Global X–Y Systems, If Calculated from***

$$F_i = \sqrt{F_{iX} + F_{iY} + F_{iZ}}$$

# Nonlinear Failure Mode For Skew Bridges




**Contact at Right Abutment**

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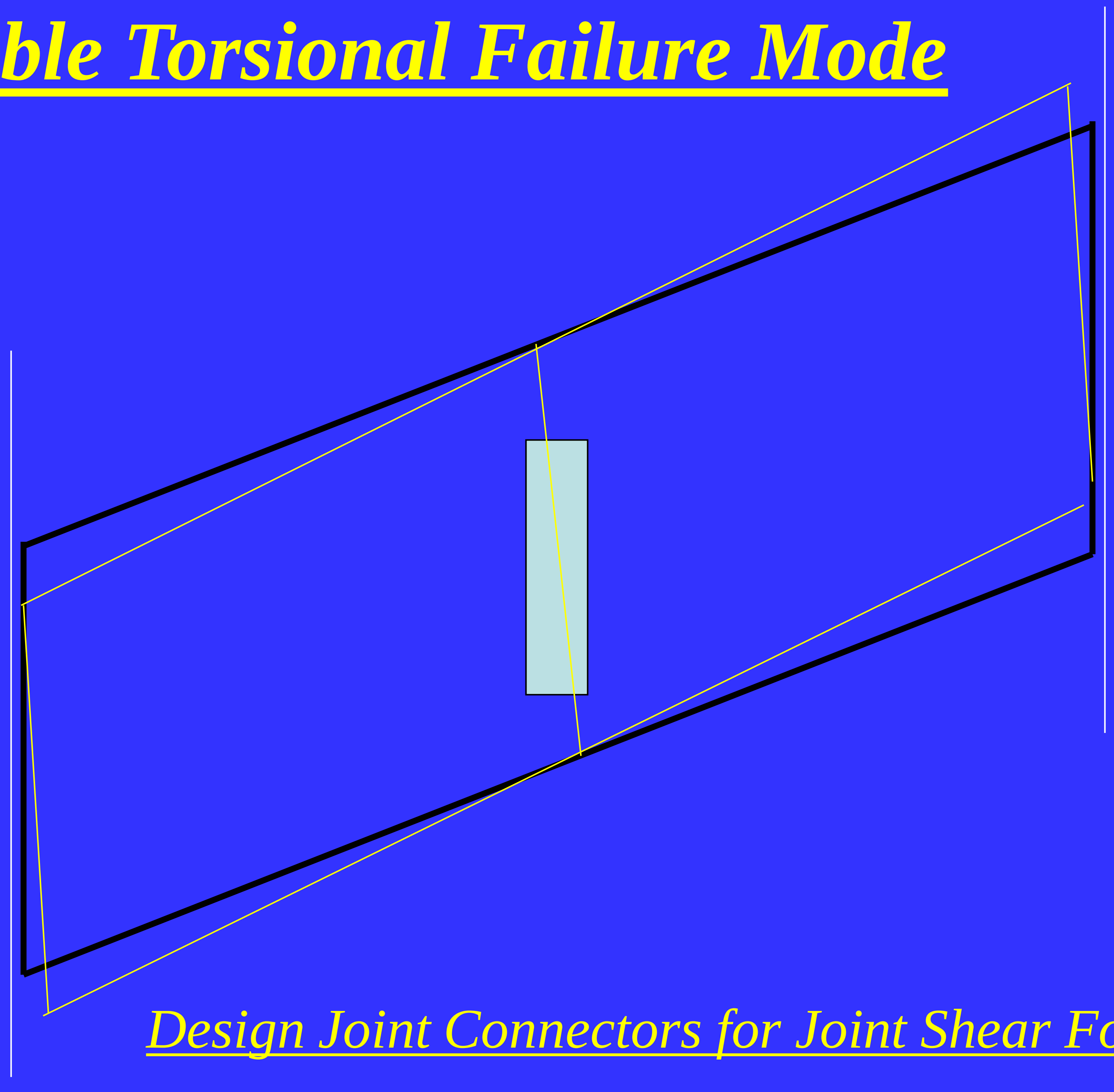
# ***Possible Torsional Failure Mode***



*Design Joint Connectors for Joint Shear Forces !*

# *Use a Global Modal for all Analyses*

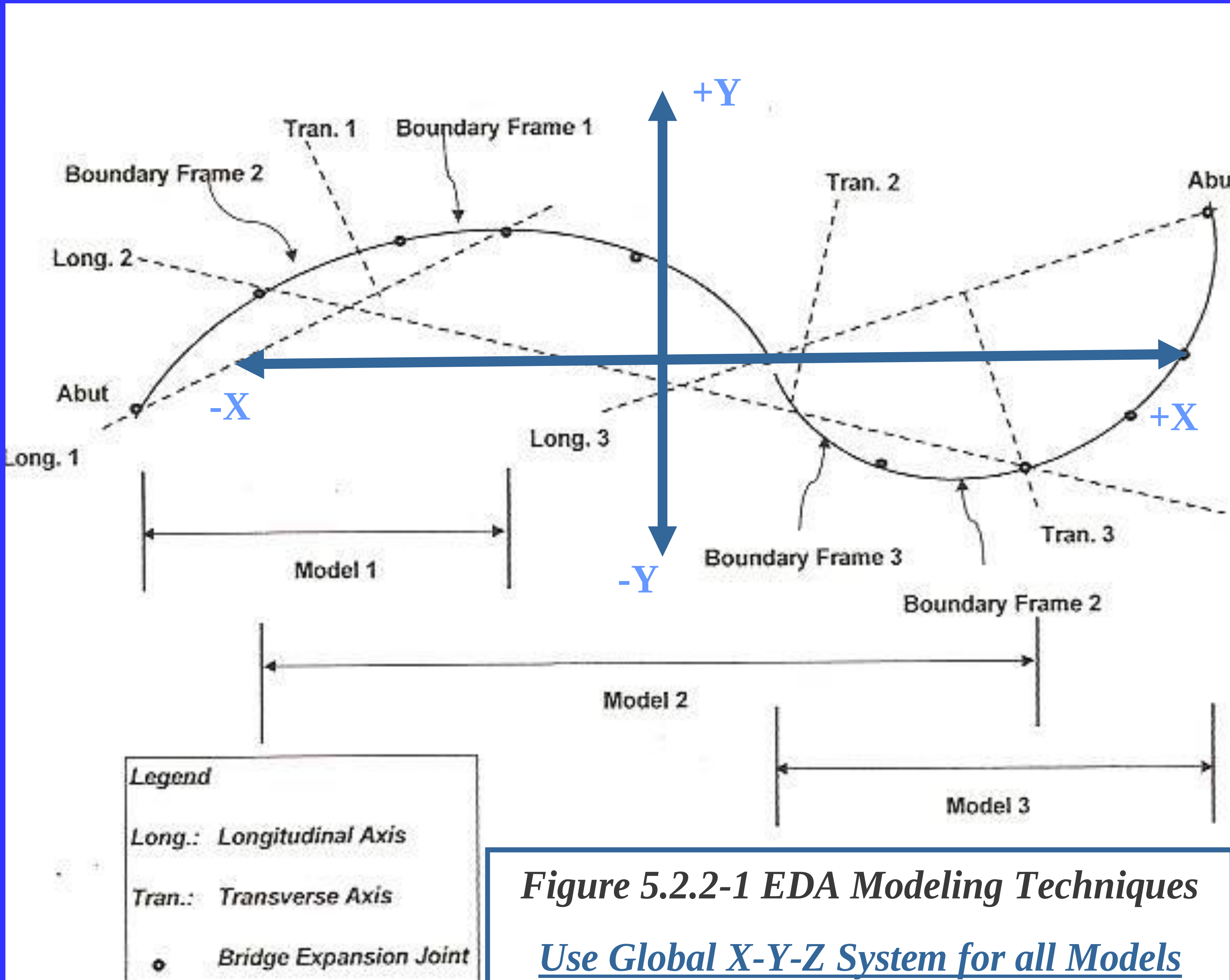



*Figure 5.2.2-1 EDA Modeling Techniques*

*Use Global X-Y-Z System for all Models*

# Equal Displacement Rule

***In 1960 Veletsos and Newmark proposed in a paper presented at the 2nd WCEE in Japan***

***For a one DOF System, subjected to the El Centro Earthquake, the Maximum Displacement was approximately the same for both linear and nonlinear analyses.***

***In 1965 Clough and Wilson, at the 3rd WCEE in Chile, proved the Equal Displacement Rule <u>did not apply</u> to multi DOF structures.***

***See edwilson.org to read paper.***

## *1965 Professor Clough's Comment*

*. "The maximum displacements from a nonlinear a dynamic analysis are significantly greater than the displacements obtained  from a linear dynamic analysis"*

## *2014 Comment by Old Ed Wilson*

*"Today, It appears the earthquake displacements at bridge joints are being predicted by the*

*Equal Displacement Rule"*

# *1965 Comments by Ray and Ed*

*"If tall buildings are designed for elastic column behavior and restrict the nonlinear bending behavior to the girders, it appears the danger of total collapse of the building is reduced."*

*This indicates the strong-column and weak beam design is the one of the first statements on*

## ***Performance Based Design***

# *Comment on the use of the Response Spectrum Method*

***I do not know who first called it a "response spectrum," but unfortunately the term leads people to think that it characterizes the building's motion, rather than the ground's motion.***

***George W. Housner***

***EERI Oral History, 1996***

***1910-2008***

# *Seismic Analysis Advice* by Ed Wilson

1. *All Structures Bridges are Three-Dimensional and their Dynamic Behavior is governed by the Mass and Stiffness Properties of the structure. The Longitudinal and Transverse directions are geometric properties. All Structures have Torsional Modes of Vibrations.*

2. *The Response Spectrum Analysis Method is a very approximate method of seismic analysis which only produces positive values of displacements and member forces which are not in equilibrium. Demand -Capacity Ratios have Very Large Errors*

3. *Short and Long Duration earthquakes are treated by using the same "Design Spectra". Results are maximum probable values and occur at an "Unknown Time".*

4. *The Engineer does not gain insight into the "Dynamic Behavior of the Structure"*

# *"Linear Dynamic Response Analysis"*

*It is a simple extension of Static Analysis – just add mass and time dependent loads*

1. *Static and Dynamic Equilibrium is satisfied at all points in time if all modes are included*
2. *Errors in the results can be estimated automatically if modes are truncated*
3. *Time-dependent plots and animation are impressive and fun to produce*
4. *Demand /Capacity Ratios are accurate and a function of time – summarized by program.*
5. *Engineers can gain great insight into the dynamic response of the structure and may help in the redesign of the structural system.*

# *Convince Yourself with a simple test problem*

1. *Select an existing Sap 2000 model of an Ordinary Standard Bridge with several different spans – both straight and curved.*
2. *Select a 3D earthquake ground acceleration record to be used as the input loading which is approximately 20 seconds long.*
3. *Create a spectra from the selected earthquake ground acceleration record.*
4. *Using a number of modes that captures a least 90 percent of the mass in all three directions.*
5. *At any angle, Run a Linear Time History Analysis and a Response Spectrum Analysis.*
6. *Compare Demand Capacity Ratios for both SAP 2000 analyses for all members.*
7. *You decide if the Approximate RSA results are in good agreement with the Linear time History Results.*

End of Bridge Lecture

***Teaching***

***Casper, Phillips and Associates in Tacoma***

***Nonlinear Dynamic Analysis***

***Over the Telephone***

***In Six Weeks***

# ***Response Spectrum Method***

# Basic Equations in Earthquake Engineering

$$m\ddot{u}_a(t) + c\dot{u}_r(t) + ku_r(t) = 0$$

$$Basic\ Assumption\ in\ Eq.\ Eng. \quad \ddot{u}_a = \ddot{u}_g + \ddot{u}_r$$

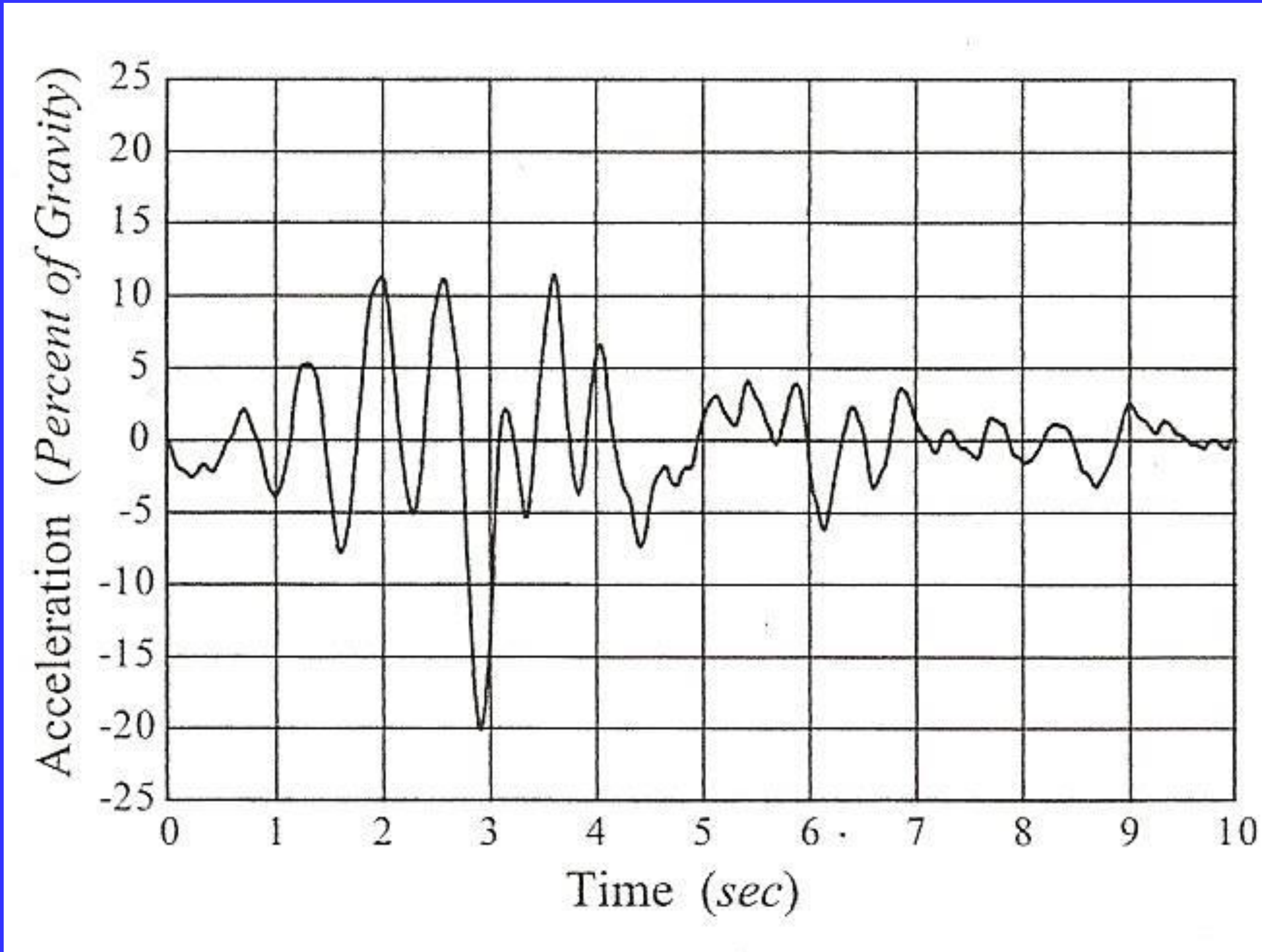
$$m\ddot{u}_r(t) + c\dot{u}_r(t) + ku_r(t) = -mu_g(t)$$

***This assumes a rigid foundation and structure.***

***In the real world, which we all live in, the horizontal <u>Earthquake Displacements Propagate</u> from the foundation <u>Upward into the Structure</u>.***

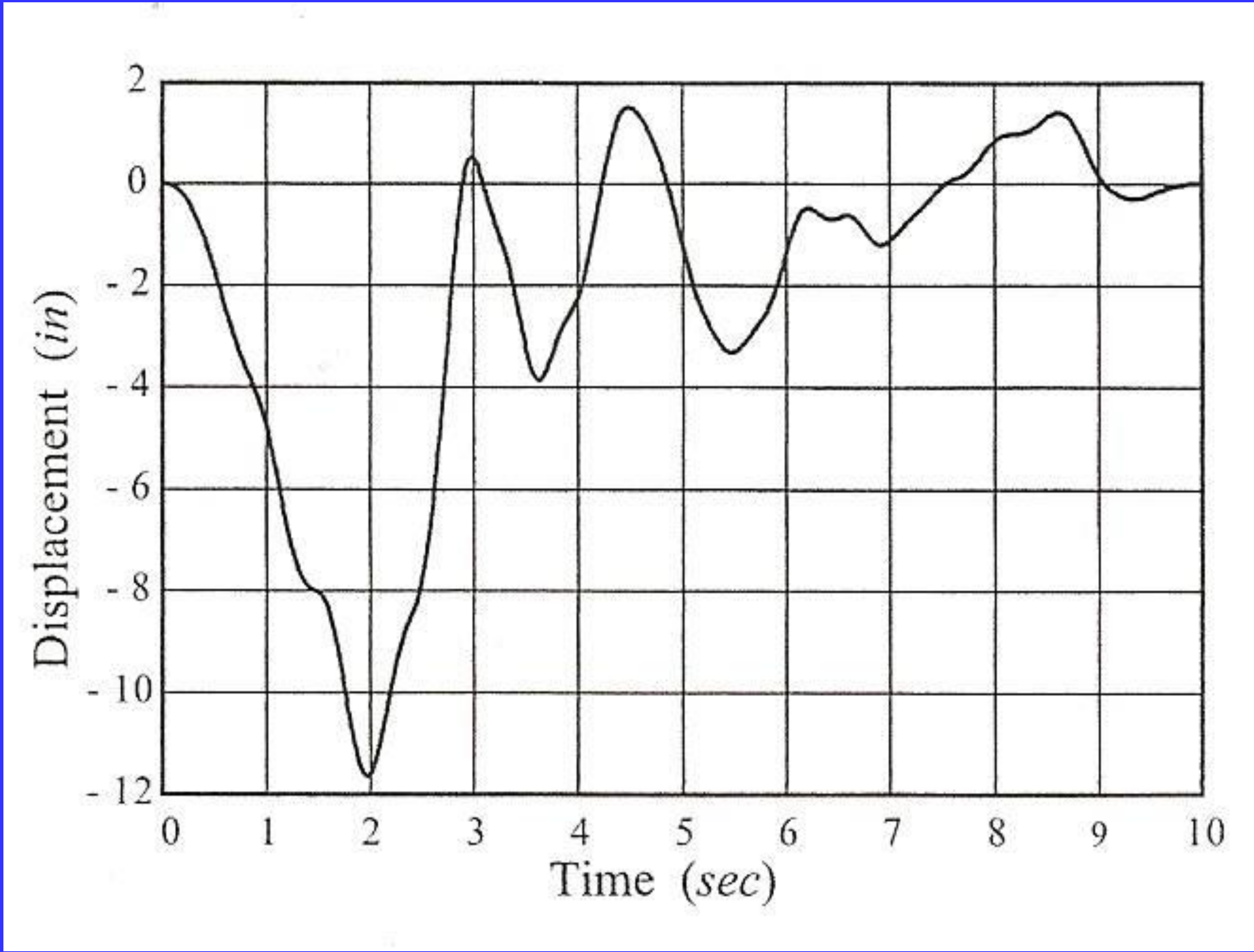
## ***WHY DO WE DO A PUSHOVER ANALYSIS?***

# *How we Calculate a Response Spectra Today*

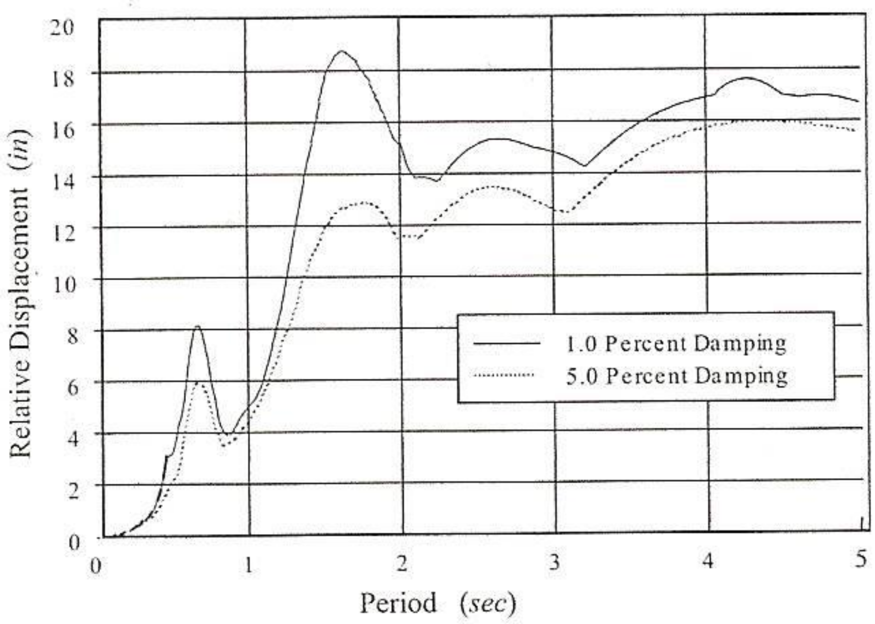



***Typical Earthquake Ground Acceleration – percent of gravity***

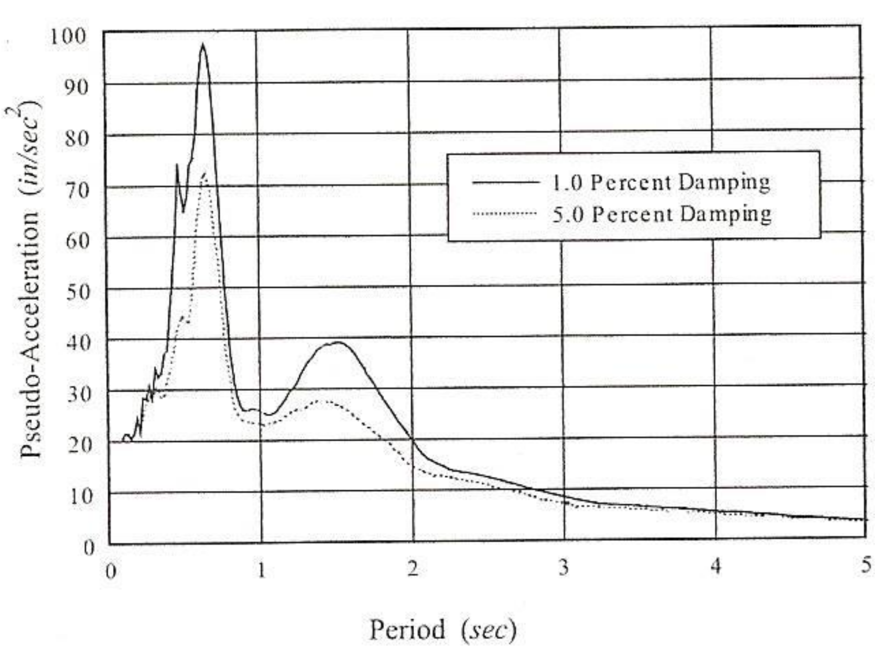
# *Integration will produce Earthquake Ground Displacement – inches*




***These real Eq. Displacement can be used as Computer Input***




(a) Relative Displacement Spectrum, $y_{\max}(\omega)$




(b) Pseudo-Acceleration Spectrum, $S_a = \omega^2\, y_{\max}(\omega)$

## *Relative Displacement Spectrum for a unit mass with different periods*

1. *These displacements $u_{max}$ are maximum (+ or -) values versus period for a structure or mode.*
2. *Note: we do not know the time these maximums took place.*

## *Pseudo Acceleration Spectrum*

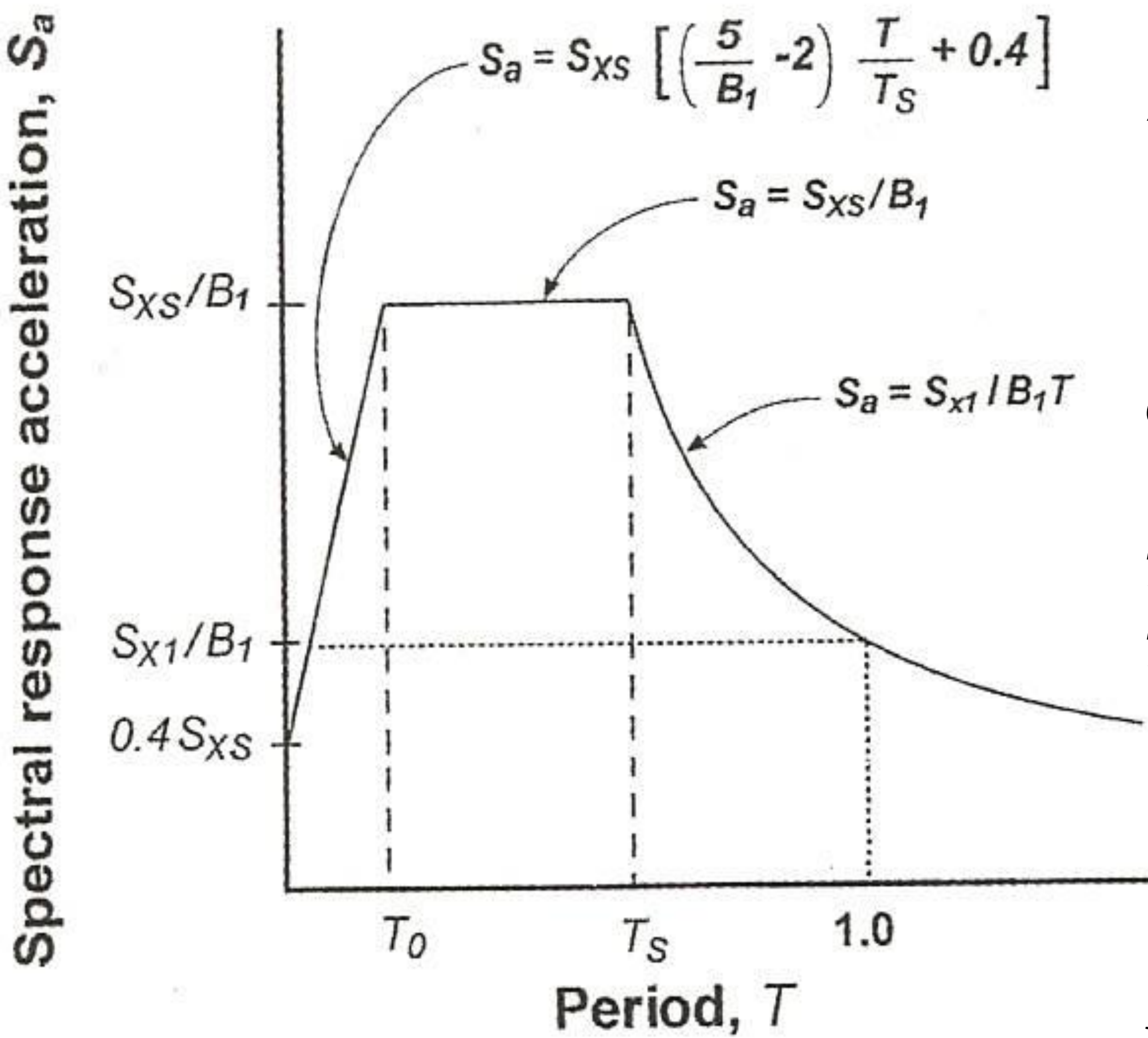
*Note: $S = w^2\, u_{max}$ has the same properties as the Displacement Spectrum. Therefore, how can anyone justify combining values, which occur at different times, and expect to obtain accurate results.*

## *Random Vibrations?*

***t = ± infinity Also site effects***

# General Horizontal Response Spectrum

## from ASCE 41- 06




**Simple User Defined Data**

$\beta = effective\ viscous ratio$

$S_{xs} = peak\ base\ acceleration$

$S_{x1} = value at\ 1.0\ sec\ period$

**Constants to be Calculated**

$B_1 = 4[5.6 - \ln(100\beta)$

$T_s = S_{x1} / S_{sx}$

$T_0 = 0.2T_s$

**Duration has been Neglected**

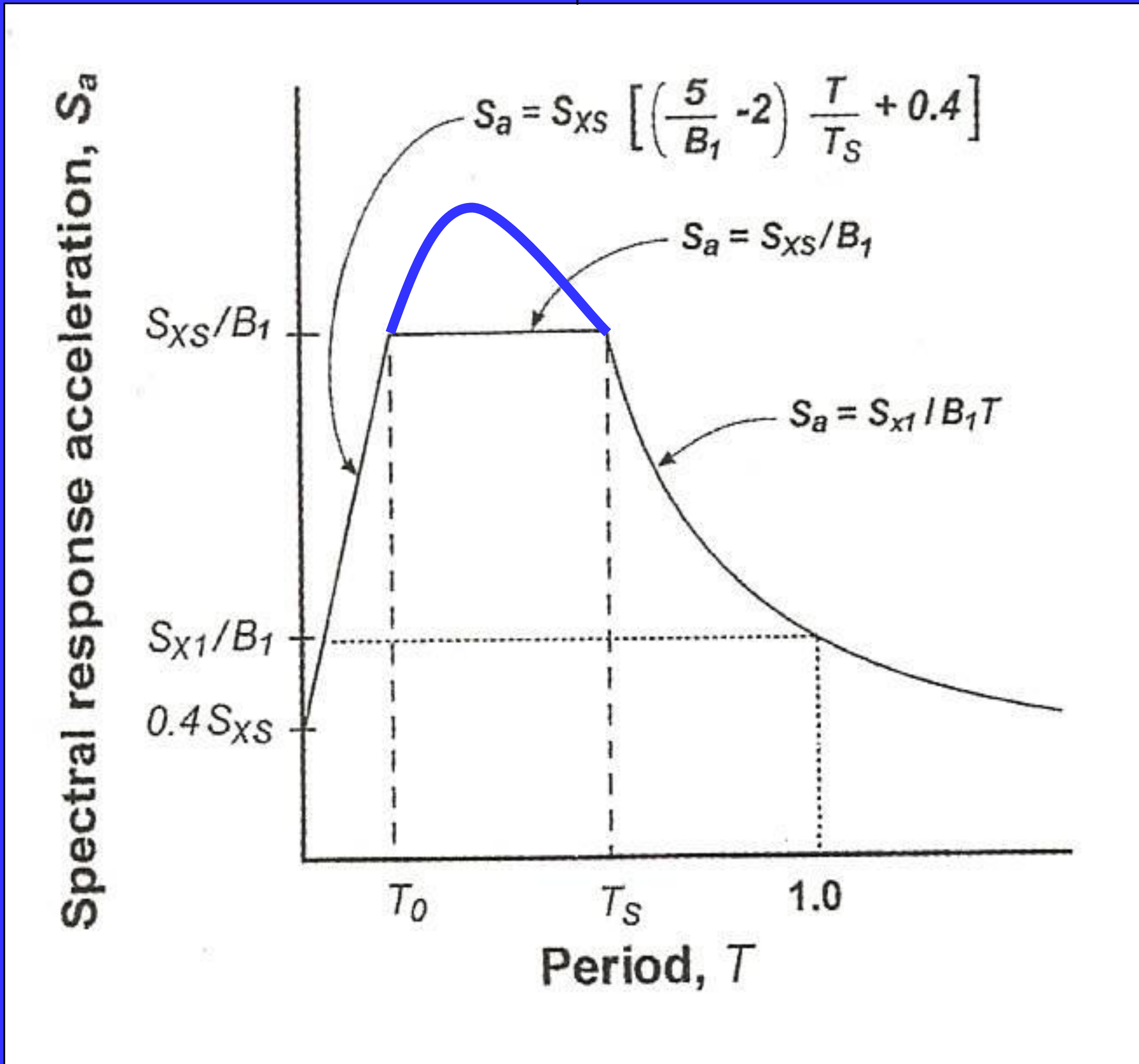
**Shape is not Realistic**

**NonLinear Structures - No**

**Where did the hat go?**

# Where did the Hat go - on the Response Spectrum ?

## As I Recall -------



# *Demand-Capacity Ratios*

*The Demand-Capacity ratio for a linear elastic compression member is given by an equation of the following general form:*

$$R(t) = \frac{|P(t)|}{\phi_c P_{cr}} \pm \frac{M_2(t)C_2}{\phi_b M_{c2}\left(1 - \frac{|P(t)|}{P_{e2}}\right)} \pm \frac{M_3(t)C_3}{\phi_b M_{c3}\left(1 - \frac{|P(t)|}{P_{e3}}\right)} \le 1.0$$

*If the axial force and the two moments are a function of time, the Demand-Capacity ratio will be a function of time and a smart computer program will produce R(max) and the time it occurred.*

***<u>A smart engineer will hand check several of these values</u>.***

# RSM Demand-Capacity Ratios

*If the axial force and the two moments are produced by the Response Spectrum Method the Demand-Capacity ratio may be computed by an equation of the following general form:*

$$R(max) = \frac{|P(max)|}{\phi_c P_{cr}} + \left| \frac{M_2(max) C_2}{\phi_b M_{c2}\left(1 - \frac{|P(max)|}{P_{e2}}\right)} \right| + \left| \frac{M_3(max) C_3}{\phi_b M_{c3}\left(1 - \frac{|P(max)|}{P_{e3}}\right)} \right| \leq 1.0$$

*Structural Analysis Programs can compute and display this Demand-Capacity Ratio.*

**However, anyone who believes it does not have**

## **Common Sense**

***SPEED and COST of COMPUTERS***

***1957 to 2014  to the Cloud***

# 1957 My First Computer in Cory Hall

# IBM 701 Vacuum Tube Digital Computer

## Could solve 40 equations in 30 minutes

*In 1959 the campus got a IBM 704 with Floating Point hardware and more fast memory – it was a joy to program*

# *1981 My First Computer Assembled at Home*

*Paid $6000 for a 8 bit CPM Operating System with FORTRAN.*

*Used it to move programs from the CDC 6400 to the VAX on Campus.*

*Developed a new program called SAP 80 without using any Statements from previous versions of SAP.*

*After two years, system became obsolete when IBM released DOS with floating point chip.*

*In 1984, CSI developed Graphics and Design Post-Processor and started distribution of the Professional Version of Sap 80*

# *Floating-Point Speeds of Computer Systems*

**Definition of one Operation A = B + C*D 64 bits - REAL*8**

| *Year* | *Computer or CPU* | *Operations Per Second* | *Relative Speed* |
|---|---|---|---|
| 1963 | CDC-6400 | 50,000 | 1 |
| 1964 | CDC-6600 | 100,000 | 2 |
| 1974 | CRAY-1 | 3,000,000 | 60 |
| 1981 | IBM-3090 | 20,000,000 | 400 |
| 1981 | CRAY-XMP | 40,000,000 | 800 |
| 1994 | Pentium-90 | 3,500,000 | 70 |
| 1995 | Pentium-133 | 5,200,000 | 104 |
| 1995 | DEC-5000 upgrade | 14,000,000 | 280 |
| 1998 | Pentium II - 333 | 37,500,000 | 750 |
| 1999 | Pentium III - 450 | 69,000,000 | 1,380 |

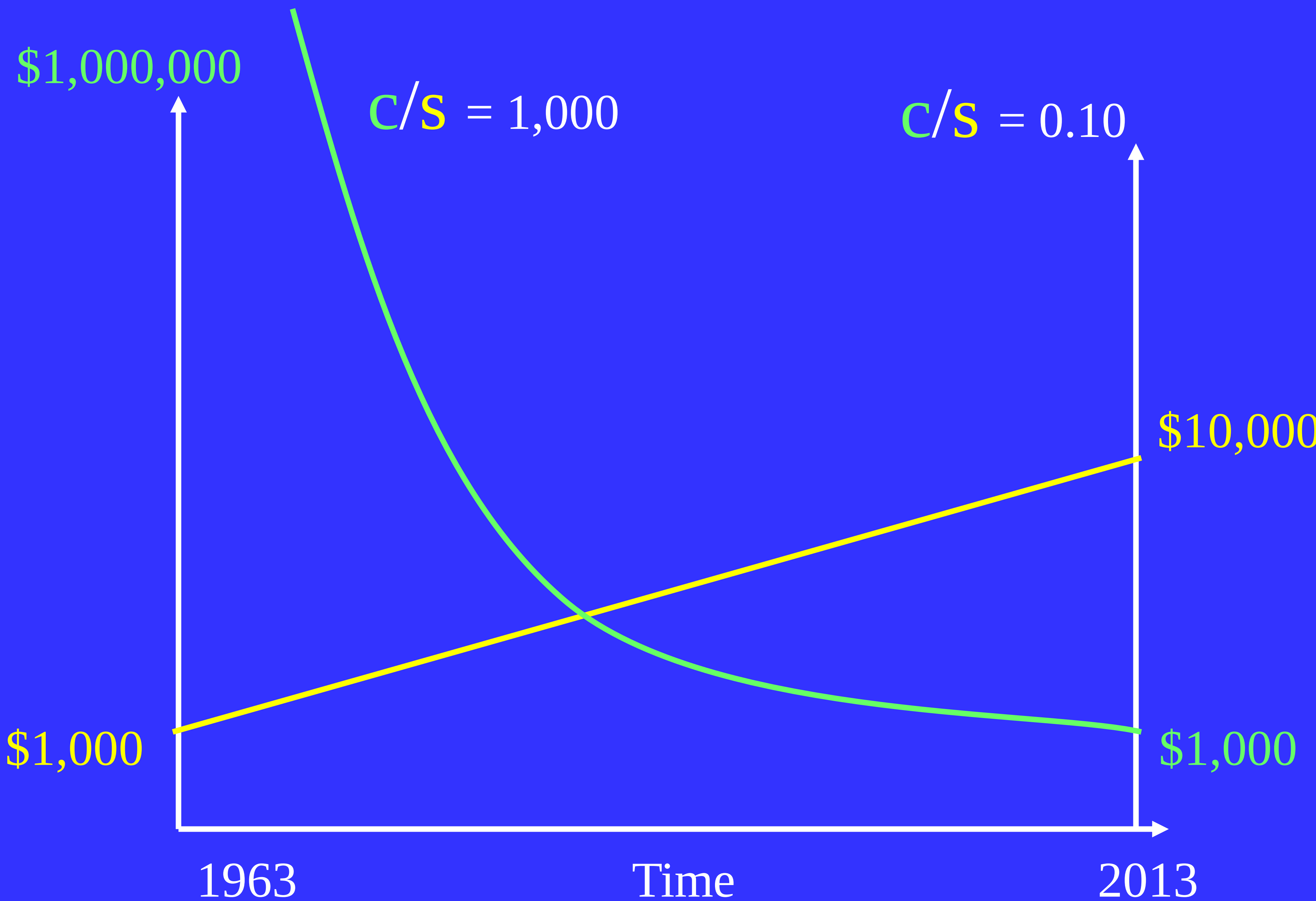
# ***Cost of Personal Computer Systems***

| YEAR | CPU | Speed MHz | Operations Per Second | Relative Speed | COST |
|---|---|---|---|---|---|
| 1980 | 8080 | 4 | 200 | 1 | $6,000 |
| 1984 | 8087 | 10 | 13,000 | 65 | $2,500 |
| 1988 | 80387 | 20 | 93,000 | 465 | $8,000 |
| 1991 | 80486 | 33 | 605,000 | 3,025 | $10,000 |
| 1994 | 80486 | 66 | 1,210,000 | 6,050 | $5,000 |
| 1996 | Pentium | 233 | 10,300,000 | 52,000 | $4,000 |
| 1997 | Pentium II | 233 | 11,500,000 | 58,000 | $3,000 |
| 1998 | Pentium II | 333 | 37,500,000 | 198,000 | $2,500 |
| 1999 | Pentium III | 450 | 69,000,000 | 345,000 | $1,500 |
| 2003 | Pentium IV | 2000 | 220,000,000 | 1.100,000 | $2.000 |
| 2006 | AMD - Athlon | 2000 | 440,000,000 | 2,200,000 | $950 |

| Year | Computer or CPU | Cost | Operations Per Second | Relative Speed |
|---|---|---|---|---|
| ***1963*** | ***CDC-6400*** | ***$1,000,000*** | ***50,000*** | ***1*** |
| *1974* | *CRAY-1* | *$4,000,000* | *3,000,000* | *60* |
| *1981* | *VAX or Prime* | *$100,000* | *100,000* | *2* |
| *1994* | *Pentium-90* | *$5,000* | *4,000,000* | *70* |
| *1999* | *Intel Pentium III-450* | *$1,500* | *69,000,000* | *1,380* |
| *2006* | *AMD 64 Laptop* | *$2,000* | *400,000,000* | *8,000* |
| *2009* | *Min Laptop* | *$300* | *200,000,000* | *4,000* |
| 2010 | *2.4 GHz Intel Core i3 64 bit Win 7 Laptop* | $1,000 | *1.35 Billion* ***Intel Fortran*** | *27,000* |
| *2013* | *2.80 GHz 2 Quad Core 64 bit Win 7* | *$1,000* | *2.80 Billion Parallelized Fortran* | *56,000* |

***The cost of one operation has been reduced by 56 Billion in the last 50 years***

# *Computer Cost versus Engineer's Monthly Salary*



*NOW - You can now buy a very Fast  computer for less than $1,000*

***However***

***If it has a new operating system***

*It may cost you <u>Several thousand dollars</u> of your time to learn how to use all the new options.*

*Also, you will need to buy new computer <u>Software from Microsoft</u>*

SPEED
60 years ago
April 17, 1954

Cal vs UCLA
Track Meet

Ed set a meet Record
in the 880 Yd Race

UC President
Robert G Sproul
held the tape

# S A P

# STRUCTURAL ANALYSIS PROGRAM

## ALSO A PERSON

*" Who Is Easily Deceived Or Fooled"*

*" Who Unquestioningly Serves Another"*

# From The Foreword Of The First SAP Manual

*"The slang name S A P was selected to remind the user that this program, like all programs, lacks intelligence.*

*It is the responsibility of the engineer to idealize the structure correctly and assume responsibility for the results."*

*Ed Wilson 1970*

# The SAP Series of Programs

| | | |
|---|---|---|
| *1969 - 70* | *SAP* | *Used Static Loads to Generate Ritz Vectors* |
| *1972 -73* | *SAP IV* | *Subspace Iteration – Dr. Jűgen Bathe* |
| *1973 – 74* | *NON SAP* | *New Program – The Start of ADINA* |
| | | ***Gave FORTRAN programs away*** |
| *1980 – 82* | *SAP 80* | *New Linear Program for Personal Computers* |

## *Lost All Research and Development Funding*

| | | |
|---|---|---|
| *1983 – 1987* | *SAP 80* | *CSI added Pre and Post Processing* |
| *1987 - 1990* | *SAP 90* | *Significant Modification and Documentation* |
| *1997 – 2000* | *SAP 2000* | *Nonlinear Elements – More Options – With Windows Interface* |

*2001 - Ed stopped development work – could not adjust to Windows*

*2014 – CSI Continues to improve programs with creativity*

# Damping and Energy Dissipation

***Inelastic Materials*** ***– Dissipation of Strain Energy***

***Friction*** ***– Energy loss proportional to displacements***

***Radiation*** ***– Kinetic and Strain Energy within a Vibrating Structure is Transferred to the Foundation***

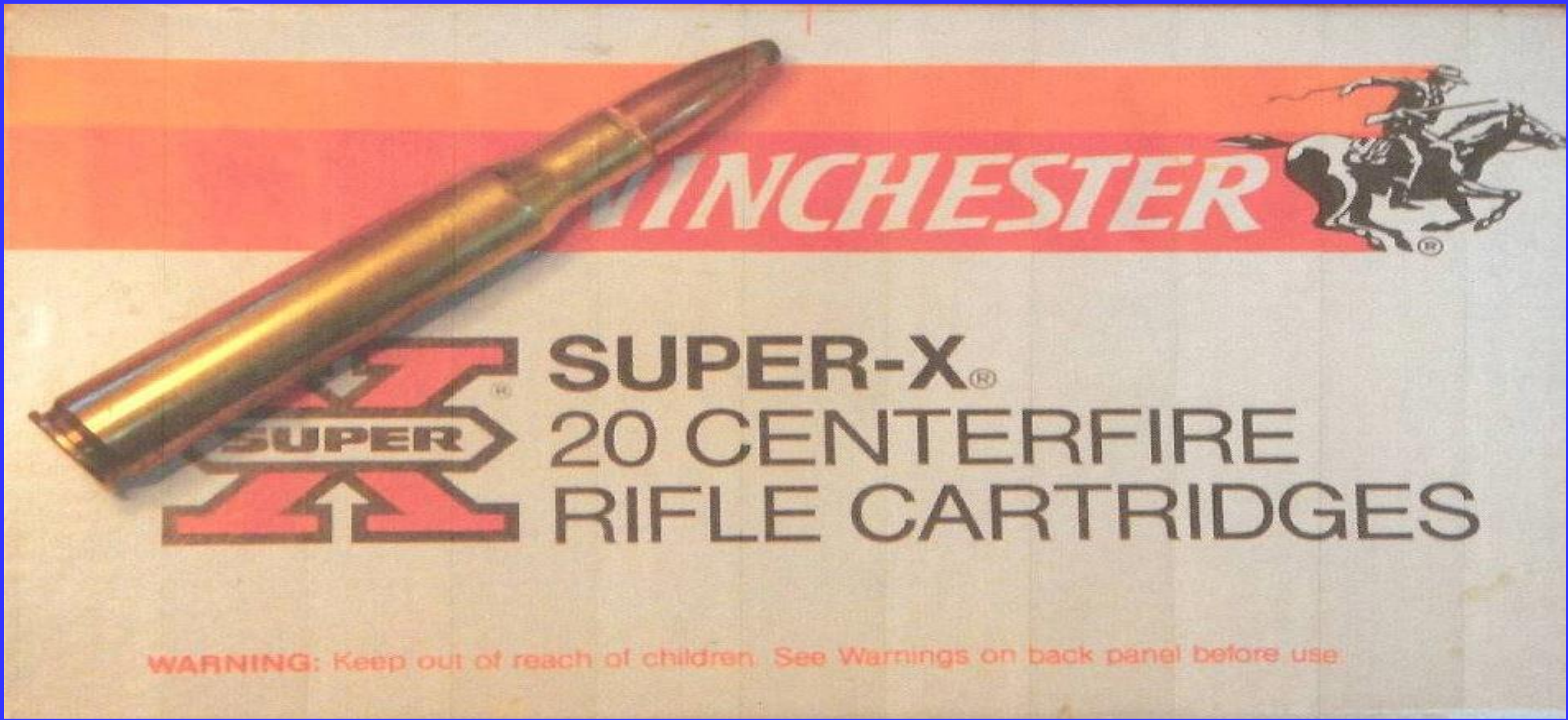
***Linear Viscous Damping*** ***– Does not exist in any human made device. Or*** $f_d$ **is not equal to** $c\dot{u}$

***Therefore, the use of Complex Variable Notation if not necessary in dynamic analysis.***

# *Structures Fail due to Strain Energy not Kinetic Energy*

***Best design will have minimum Strain Energy?***

*This type of Kinetic Energy can Kill Several Million times more people than Earthquakes*



# Terminology in nonlinear analysis
# Which does not have a unique definition

1. Equal Displacement Rule
2. Pushover Analysis
3. Equivalent Linear Damping
4. Equivalent Static Analysis
5. Nonlinear Spectrum Analysis
6. Onerous Response History Analysis

# *Approximations are Necessary*

## *However:*

1. ***Do not use a 1960 rule without verification.***
2. ***There is always a more accurate method to solve a problem.***
3. ***If a large organization uses a method it does not make it a correct method.***
4. ***After you complete a large analysis, do parameter studies, or, use another method to analyze the structure .*** ***There are 168 hours in a week.***

# ***Recommendations*** *– slide 1*

***Proposed by Ed Wilson and many others & ATC-82 Project***

***Let us be realistic, the majority of our engineering colleagues  want to use the RSM; and, we will respect their decisions.***

***Therefore, we will propose an "optional" alternative to the use of the response spectrum method.***

***The design engineer will be allowed to use 'three dimensional  time-history records" if their spectra exceeds the code values  for all periods.***

***These "spectrally matched earthquake motions" must be based on modified recorded earthquake records.***

# ***Recommendations** – slide 2*

***In addition, the maximum component of the three dimensional earthquake records must be applied in the most flexible direction of the structure, as defined by the direction of the base shear associated with the lowest frequency of the structure.***

***The same earthquake must be applied at 90 degrees to the first analysis.***

***Also, two additional spectrally matched earthquake motions of different durations must be used in two additional analyses.***

# *Recommendations* *– slide 3*

*Add + and - 5 percent static torsion load.*

*In order to include P-Delta analysis the geometric stiffness, due to vertical dead loads, will be included in the calculation of mode shapes and frequencies.*

*We believe, after a smart structural engineer does these six analyses and compares the results with the standard RSM, it will be apparent a superior and less expensive design has been produced.*

*These results will satisfy all existing Codes - NOW!*

***Thank you***