Dynamic Analysis

With Emphasis On

Wind and Earthquake Loads

BY

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Summary Of Presentation

1. General Comments

2. History Of The Development of SAP

3. Computer Hardware Developments

4. Methods For Linear and Nonlinear Analysis

5. Generation And Use Of LDR Vectors and Fast Nonlinear Analysis - FNA Method

6. Example Of Parallel Engineering Analysis of the Richmond - San Rafael Bridge
Structural Engineering Is

The Art Of Using Materials
Which We Do Not Fully Understand

To Build Structural Systems
Which Can Only Be Approximately Analyzed

To Withstand Forces
Which Are Not Accurately Known

So That We Can Satisfy
Our Responsibilities
In Regards To Public Safety
FUNDAMENTALS OF ANALYSIS

1. UNDERSTAND PHYSICS OF PROBLEM
2. CREATE COMPUTER MODEL
3. CONDUCT PARAMETER STUDIES
4. VERIFICATION OF RESULTS
   STATIC AND DYNAMIC EQUILIBRIUM
   ENERGY BALANCE
5. FIELD OR LABORATORY TESTS
FIELD MEASUREMENTS REQUIRED TO VERIFY

1. MODELING ASSUMPTIONS
2. SOIL-STRUCTURE MODEL
3. COMPUTER PROGRAM
4. COMPUTER USER
CHECK OF RIGID DIAPHRAGM APPROXIMATION

MECHANICAL VIBRATION DEVICES
<table>
<thead>
<tr>
<th>MODE</th>
<th>$T_{\text{FIELD}}$</th>
<th>$T_{\text{ANALYSIS}}$</th>
<th>Diff. - %</th>
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<tbody>
<tr>
<td>1</td>
<td>1.77 Sec.</td>
<td>1.78 Sec.</td>
<td>0.5</td>
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<tr>
<td>2</td>
<td>1.69</td>
<td>1.68</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>1.68</td>
<td>1.68</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>0.60</td>
<td>0.61</td>
<td>0.9</td>
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<tr>
<td>5</td>
<td>0.60</td>
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<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>0.59</td>
<td>0.59</td>
<td>0.8</td>
</tr>
<tr>
<td>7</td>
<td>0.32</td>
<td>0.32</td>
<td>0.2</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>11</td>
<td>0.23</td>
<td>0.32</td>
<td>2.3</td>
</tr>
</tbody>
</table>
FIRST DIAPHRAGM MODE SHAPE

15 th Period

\( T_{\text{FIELD}} = 0.16 \text{ Sec.} \)
COMPUTERS

1957 TO 1999

IBM 701 - PENTIUM III
C = Cost of Computer
S = Monthly Salary Engineer
C/S RATIO

1957 1999
$1,000,000 $1,000
$1000 $10,000

A Factor Of 10,000
Reduction In 42 Years
## Floating Point Speed Comparison

FORTRAN 64 bits - REAL*8

**Definition of one Operation**  
\[ A = B + C \times D \]

<table>
<thead>
<tr>
<th>Year</th>
<th>COMPUTER</th>
<th>Op/Sec</th>
<th>Relative Speed</th>
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<tbody>
<tr>
<td>1963</td>
<td>CDC-6400</td>
<td>50,000</td>
<td>1</td>
</tr>
<tr>
<td>1967</td>
<td>CDC-6600</td>
<td>200,000</td>
<td>4</td>
</tr>
<tr>
<td>1974</td>
<td>CRAY - 1</td>
<td>3,000,000</td>
<td>60</td>
</tr>
<tr>
<td>1980</td>
<td>VAX - 780</td>
<td>100,000-</td>
<td>2-</td>
</tr>
<tr>
<td>1981</td>
<td>CRAY-XMP</td>
<td>30,000,000</td>
<td>600</td>
</tr>
<tr>
<td>1988</td>
<td>Intel 80387</td>
<td>100,000</td>
<td>2</td>
</tr>
<tr>
<td>1990</td>
<td>DEC-5000</td>
<td>3,500,000</td>
<td>70</td>
</tr>
<tr>
<td>1994</td>
<td>Pentium 90</td>
<td>3,500,000</td>
<td>70</td>
</tr>
<tr>
<td>1995</td>
<td>DEC - ?</td>
<td>14,500,000</td>
<td>280</td>
</tr>
<tr>
<td>1997</td>
<td>Pentium Pro</td>
<td>10,000,000</td>
<td>200</td>
</tr>
<tr>
<td>1998</td>
<td>Pentium II</td>
<td>17,000,000</td>
<td>350</td>
</tr>
<tr>
<td>1999</td>
<td>Pentium III</td>
<td>45,000,000</td>
<td>900</td>
</tr>
</tbody>
</table>
### Floating Point Speed Comparison - PC

**Microsoft FORTRAN 64 bits - REAL*8**

**Definition of one Operation**  \( A = B + C \times D \)

<table>
<thead>
<tr>
<th>Year</th>
<th>CPU</th>
<th>Speed MHz</th>
<th>Op/Sec</th>
<th>Normalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>8080</td>
<td>4</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>1984</td>
<td>8087</td>
<td>10</td>
<td>13,000</td>
<td>65</td>
</tr>
<tr>
<td>1988</td>
<td>80387</td>
<td>20</td>
<td>93,000</td>
<td>465</td>
</tr>
<tr>
<td>1991</td>
<td>80486</td>
<td>33</td>
<td>605,000</td>
<td>3,025</td>
</tr>
<tr>
<td>1994</td>
<td>PENTIUM</td>
<td>66</td>
<td>1,210,000</td>
<td>6,050</td>
</tr>
<tr>
<td>1996</td>
<td>PENTIUM</td>
<td>133</td>
<td>5,200,000</td>
<td>26,000</td>
</tr>
<tr>
<td>1996</td>
<td>Pentium-Pro</td>
<td>200</td>
<td>10,000,000</td>
<td>50,000</td>
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<tr>
<td>1998</td>
<td>Pentium II</td>
<td>333</td>
<td>17,000,000</td>
<td>85,000</td>
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<tr>
<td>1999</td>
<td>Pentium III</td>
<td>450</td>
<td>45,000,000</td>
<td>225,000</td>
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</table>
The Sap Series

Structural Analysis Programs

1969 To 1999
S A P
STRUCTURAL ANALYSIS PROGRAM
ALSO A PERSON
“Who Is Easily Deceived Or Fooled”
“Who Unquestioningly Serves Another”
"The slang name SAP 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

<table>
<thead>
<tr>
<th>Year</th>
<th>Program</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>SAP</td>
<td>With User Defined Ritz Vectors</td>
</tr>
<tr>
<td>1971</td>
<td>SOLID SAP</td>
<td>For Static Loads Only</td>
</tr>
<tr>
<td>1972</td>
<td>SAP IV</td>
<td>With Full Dynamic Response</td>
</tr>
<tr>
<td>1973</td>
<td>NONSAP</td>
<td>Now ADINA</td>
</tr>
<tr>
<td>1980</td>
<td>SAP 80</td>
<td><strong>NEW</strong> Program for PC, Elements and Methods</td>
</tr>
<tr>
<td>1983</td>
<td>SAP 80</td>
<td><strong>CSI</strong> Added Pre and Design Post Processing</td>
</tr>
<tr>
<td>1989</td>
<td>SAP 90</td>
<td>Large Capacity on PC</td>
</tr>
<tr>
<td>1991</td>
<td>SADSAP</td>
<td>R &amp; D Program With Nonlinear Elements</td>
</tr>
<tr>
<td>1997</td>
<td>SAP 2000</td>
<td>Added Graphical User Interface</td>
</tr>
</tbody>
</table>
STATIC AND DYNAMIC STRUCTURAL ANALYSIS PROGRAM
How Can Engineers Be Convinced To Use New And Improved Methods Of Analysis?

1. Give Them New Capabilities Such As 2 and 3d Nonlinear Analyses

2. Or, The Program Must Be Easy To Use, Fast On A PC, And Have FANCY COLORED GRAPHICS

SAP2000
A Good Computer Program

1. The Fundamental Equations Must Represent The Real Physical Behavior Of The Structure

2. Accurate, Efficient And Robust Numerical Methods Must Be Used

3. Must Be Programmed In Portable Language In Order To Justify Development Cost

4. Must Have User-friendly Pre And Post Processors

5. Ability To PLOT All Possible Dynamic Results As A Function of TIME - Only SAP 2000 Has This Option
Numerical Methods for The Seismic Analysis of Linear and Nonlinear Structural Systems
DYNAMIC EQUILIBRIUM EQUATIONS

\[ Ma + Cv + Ku = F(t) \]

- \( a \) = Node Accelerations
- \( v \) = Node Velocities
- \( u \) = Node Displacements
- \( M \) = Node Mass Matrix
- \( C \) = Damping Matrix
- \( K \) = Stiffness Matrix
- \( F(t) \) = Time-Dependent Forces
PROBLEM TO BE SOLVED

\[ M_a + C_v + K_u = \sum f_ig(t)_i \]

\[ = -M_xa_x - M_ya_y - M_za_z \]

For 3D Earthquake Loading

THE OBJECTIVE OF THE ANALYSIS IS TO SOLVE FOR ACCURATE DISPLACEMENTS and MEMBER FORCES
METHODS OF DYNAMIC ANALYSIS

For Both Linear and Nonlinear Systems

- STEP BY STEP INTEGRATION - $0, \ dt, \ 2\ dt \ldots \ N\ dt$
- USE OF MODE SUPERPOSITION WITH EIGEN OR LOAD-DEPENDENT RITZ VECTORS FOR FNA

For Linear Systems Only

- TRANSFORMATION TO THE FREQUENCY DOMAIN and FFT METHODS
- RESPONSE SPECTRUM METHOD - CQC - SRSS
STEP BY STEP SOLUTION METHOD

1. Form Effective Stiffness Matrix

2. Solve Set Of Dynamic Equilibrium Equations For Displacements At Each Time Step

3. For Non Linear Problems Calculate Member Forces For Each Time Step and Iterate for Equilibrium - Brute Force Method
MODE SUPERPOSITION METHOD

1. Generate Orthogonal Dependent Vectors And Frequencies

2. Form Uncoupled Modal Equations And Solve Using An Exact Method For Each Time Increment.

3. Recover Node Displacements As a Function of Time

4. Calculate Member Forces As a Function of Time
GENERATION OF LOAD DEPENDENT RITZ VECTORS

1. Approximately Three Times Faster Than The Calculation Of Exact Eigenvectors

2. Results In Improved Accuracy Using A Smaller Number Of LDR Vectors

3. Computer Storage Requirements Reduced

4. Can Be Used For Nonlinear Analysis To Capture Local Static Response
STEP 1. INITIAL CALCULATION

A. TRIANGULARIZE STIFFNESS MATRIX

B. DUE TO A BLOCK OF STATIC LOAD VECTORS, $f$, SOLVE FOR A BLOCK OF DISPLACEMENTS, $u$, $Ku = f$

C. MAKE $u$ STIFFNESS AND MASS ORTHOGONAL TO FORM FIRST BLOCK OF LDL VECTORS $V_1$

$V_1^T M V_1 = I$
STEP 2. VECTOR GENERATION

\[ i = 2 \ldots N \] Blocks

A. Solve for Block of Vectors, \( K X_i = M V_{i-1} \)

B. Make Vector Block, \( X_i \), Stiffness and Mass Orthogonal - \( Y_i \)

C. Use Modified Gram-Schmidt, Twice, to Make Block of Vectors, \( Y_i \), Orthogonal to all Previously Calculated Vectors - \( V_i \)
STEP 3. MAKE VECTORS
STIFFNESS ORTHOGONAL

A. SOLVE Nb x Nb Eigenvalue Problem

\[
[ V^T K V ] Z = [ w^2 ] Z
\]

B. CALCULATE MASS AND STIFFNESS ORTHOGONAL LDR VECTORS

\[ V_R = V Z = \Phi \]
DYNAMIC RESPONSE OF BEAM

FORCE

TIME

100 pounds

10 AT 12" = 240"
## MAXIMUM DISPLACEMENT

<table>
<thead>
<tr>
<th>Number of Vectors</th>
<th>Eigen Vectors</th>
<th>Load Dependent</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.004572</td>
<td>0.004726 (+0.88)</td>
</tr>
<tr>
<td>2</td>
<td>0.004572</td>
<td>0.004591 (-2.00)</td>
</tr>
<tr>
<td>3</td>
<td>0.004664</td>
<td>0.004689 (+0.08)</td>
</tr>
<tr>
<td>4</td>
<td>0.004664</td>
<td>0.004685 (+0.06)</td>
</tr>
<tr>
<td>5</td>
<td>0.004681</td>
<td>0.004685 (0.00)</td>
</tr>
<tr>
<td>7</td>
<td>0.004683</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.004685</td>
<td></td>
</tr>
<tr>
<td>Number of Vectors</td>
<td>Eigen Vectors</td>
<td>Load Dependent</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Vectors</td>
<td>( - 22.8 %)</td>
<td>( + 9.2 )</td>
</tr>
<tr>
<td>1</td>
<td>4178</td>
<td>5907</td>
</tr>
<tr>
<td>2</td>
<td>( - 22.8 )</td>
<td>5563</td>
</tr>
<tr>
<td>3</td>
<td>( - 8.5 )</td>
<td>5603</td>
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<tr>
<td>4</td>
<td>( - 8.5 )</td>
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<td>( - 4.1 )</td>
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<td>7</td>
<td>( - .0 )</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>( 0.0 )</td>
<td></td>
</tr>
</tbody>
</table>

( Error in Percent )
Push Over Analysis

1. One-dimensional Static Loads
2. No Energy Dissipation
3. Inertia Forces Not Considered
4. Defines One Failure Mode
5. Higher Mode Effects Neglected
1. Evaluate LDR vectors with nonlinear elements removed and dummy elements added for stability.

2. Solve all modal equations with nonlinear forces on the right hand side.

3. Use exact integration within each time step.

4. Force and energy equilibrium are satisfied at each time step by iteration.
The FNA Method Is Designed For The Static And Dynamic Analysis Of Nonlinear Structures With A Limited Number Of Predefined Nonlinear Elements
BASE ISOLATION

Isolators
BUILDING IMPACT ANALYSIS
FRICTION DEVICE

CONCENTRATED DAMPER

NONLINEAR ELEMENT
PLASTIC HINGES

2 ROTATIONAL DOF

DEGRADING STIFFNESS?
Mechanical Damper

Mathematical Model

\[ F = f(u, v, u_{\text{max}}) \]

\[ F = ku \]

\[ F = C v^N \]
LINEAR VISCOUS DAMPING

DOES NOT EXIST IN NORMAL STRUCTURES AND FOUNDATIONS

5 OR 10 PERCENT MODAL DAMPING VALUES ARE OFTEN USED TO JUSTIFY ENERGY DISSIPATION DUE TO NONLINEAR EFFECTS

IF ENERGY DISSIPATION DEVICES ARE USED THEN 1 PERCENT MODAL DAMPING SHOULD BE USED FOR THE ELASTIC PART OF THE STRUCTURE - CHECK ENERGY PLOTS
103 FEET DIAMETER - 100 FEET HEIGHT

ELEVATED WATERSTORAGE TANK

NONLINEAR DIAGONALS
BASE ISOLATION
COMPUTER MODEL

92 NODES

103 ELASTIC FRAME ELEMENTS

56 NONLINEAR DIAGONAL ELEMENTS

600 TIME STEPS @ 0.02 Seconds
## COMPUTER TIME REQUIREMENTS

<table>
<thead>
<tr>
<th>PROGRAM</th>
<th>MACHINE</th>
<th>TIME</th>
<th>TOTAL MINUTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANSYS</td>
<td>INTEL 486</td>
<td>3 Days</td>
<td>4300 Minutes</td>
</tr>
<tr>
<td>ANSYS</td>
<td>CRAY</td>
<td>3 Hours</td>
<td>180 Minutes</td>
</tr>
<tr>
<td>SADSAP</td>
<td>INTEL 486</td>
<td></td>
<td>2 Minutes</td>
</tr>
</tbody>
</table>

( B Array was 56 x 20 )
Nonlinear Equilibrium Equations

\[ M a + C v + Ku + F_N = F \]

Or

\[ M a + C v + Ku = F - F_N \]

Where

\[ F_N = \text{The Global Node Loads due to the Forces in the Nonlinear Elements} \]
Nonlinear Equilibrium Equations

\[ M \ddot{a} + C \dot{v} + \left[ K + k_E \right] u = F - F_N + k_E u \]

Where

\[ k_E = \text{The Effective Linear Stiffness} \]

of the Nonlinear Elements are of arbitrary values for zero damping.
1. Calculate Ritz Vectors for Structure With the Nonlinear Elements Removed.

2. These Vectors Satisfy the Following Orthogonality Properties

\[ \phi^T K \phi = \Omega^2 \quad \phi^T M \phi = I \]
3. The Solution Is Assumed to Be a Linear Combination of the LDR Vectors. Or,

\[ u(t) = \Phi \ Y(t) = \sum_{n} \Phi_n \ y(t)_n \]

Which Is the Standard Mode Superposition Equation

Remember the LDR Vectors Are a Linear Combination of the Exact Eigenvectors; Plus, the Static Displacement Vectors.

No Additional Approximations Are Made.
4. A typical modal equation is uncoupled. However, the modes are coupled by the unknown nonlinear modal forces which are of the following form:

\[ f_n = \phi_n F_n \]

5. The deformations in the nonlinear elements can be calculated from the following displacement transformation equation:

\[ \delta = A u \]
6. Since \( u(t) = \Phi Y(t) \) the deformations in the nonlinear elements can be expressed in terms of the modal response by

\[
\delta(t) = A\Phi Y(t) = BY(t)
\]

Where the size of the \( B \) array is equal to the number of deformations times the number of LDR vectors.

The \( B \) array is calculated only once prior to the start of mode integration.

THE \( B \) ARRAY CAN BE STORED IN RAM
7. The nonlinear element forces are calculated, for iteration $i$, at the end of each time step $t$

$$\delta_t^{(i)} = B Y_t^{(i)} = \text{Deformations in Nonlinear Elements}$$

$$P_t^{(i)} = \text{Function of Element History}$$

$$f_N^{(i)} = B^T Y_t^{(i)} = \text{Nonlinear Modal Loads}$$

$$Y_t^{(i+1)} = \text{New Solution of Modal Equation}$$
Four Static Load Conditions Are Used To Start The Generate of LDR Vectors
NONLINEAR STATIC ANALYSIS

50 STEPS AT $dT = 0.10$ SECONDS

LOAD

DEAD LOAD

LATERAL LOAD

TIME - Seconds
FORCE AT BASE OF RIGHT COLUMN

DAMPING = 0.99 PERCENT

TIME - SECONDS
Advantages Of The FNA Method

1. The Method Can Be Used For Both Static And Dynamic Nonlinear Analyses

2. The Method Is Very Efficient And Requires A Small Amount Of Additional Computer Time As Compared To Linear Analysis

2. The Method Can Easily Be Incorporated Into Existing Computer Programs For LINEAR DYNAMIC ANALYSIS.
FUTURE DEVELOPMENTS FOR SAP2000

1. ADDITIONAL NONLINEAR ELEMENTS
   crush and yield elements
degraded stiffness elements
general CABLE element

2. SUBSTRUCTURE OPTION

3. SOIL STRUCTURE INTERACTION

4. FULID - STRUCTURE INTERACTION

5. ADDITIONAL DOCUMENTATION AND EXAMPLES
EXAMPLE ON THE USE OF SUBSTRUCTURE ANALYSIS

LINEAR AND NONLINEAR ANALYSIS OF THE RICHMOND-SAN RAFAEL BRIDGE
Sub-Structured Model

Cantilever Truss Bridge

ICF KAISER
Richmond-San Rafael Bridge

Seg-A/Plate Girder Spans

*ICP KABER*
Stiffness Matrix
Size = 3 x 16 = 48

MASSLESS JOINT
( Eliminated DOF )

MASS POINTS and
JOINT REACTIONS
( Retained DOF )
SUBSTRUCTURE

SUBROUTINE

\[
\begin{bmatrix}
  k_{aa} & k_{ab} \\
  k_{ba} & k_{bb}
\end{bmatrix}
\]

SEE FORTRAN LISTING
ADVANTAGES IN THE USE OF SUBSTRUCTURES

1. FORM OF MESH GENERATION
2. LOGICAL SUBDIVISION OF WORK
3. MANY SHORT COMPUTER RUNS
4. RERUN ONLY SUBSTRUCTURES WHICH WERE REDESIGNED
5. PARALLEL POST PROCESSING USING NETWORKING
RICHMOND - SAN RAFAEL BRIDGE
AS BUILT
RICHMOND - SAN RAFAEL BRIDGE
RETROFIT ELEMENTS
ECCENTRICALLY BRACED FRAME
EFFECTIVE LINEAR MODEL OF FOUNDATION PILE GROUP

K(6,6) STIFFNESS MATRIX
M = ?   C = ?
NONLINEAR MODEL OF FOUNDATION PILE GROUP

\[ C_S = \frac{V_S}{m} \]

\[ C_N = \frac{V_N}{m} \]
SITE ANALYSIS - SHAKE

1. ONE-DIMENSIONAL ANALYSIS

2. EFFECTIVE MODULUS and CONSTANT VISCOUS DAMPING NOT A FUNCTION OF TIME

3. PERMANENT SET NOT POSSIBLE

4. ARE THESE APPROXIMATIONS NECESSARY? USE SAP 2000
STRUCTURAL ENGINEER'S VIEW OF SOIL-STRUCTURE SYSTEM

FEATHER Structure

RIGID BLOCK Foundation
GEOTECHNICAL ENGINEER'S VIEW OF SOIL-STRUCTURE SYSTEM

RIGID BLOCK Structure

FEATHER PILLOW Foundation
WHAT IS THE MOST SIGNIFICANT BARRIER TO PRODUCING GOOD SOLUTIONS OF SOIL-STRUCTURE INTERACTION PROBLEMS?

SITE RESPONSE AND STRUCTURAL ENGINEERING ARE CONDUCTED AT DIFFERENT LOCATIONS (OFFICES) USING DIFFERENT NUMERICAL METHODS AND APPROXIMATIONS
WIND RESPONSE OF TALL BUILDINGS
ENERGY DISSIPATION SYSTEMS

Base Isolation Or Uplift

Dampers

Plastic Hinge - Friction and Gap Elements
Dynamic Wind Analysis

1. Random Vibration
   A. Classical Approach.
   B. Linear Analysis Only

2. Time History Response
   A. Exact For Given Periodic Loading
   B. Non-linear Analysis Is Possible
   C. Can Perform Code Checks As A Function Of Time
Weakness Of The Response Spectrum Methods

\[ \frac{f_a}{F_a} + C_{mx} \frac{f_{bx}}{(1 - \frac{f_a}{F_{ex}}) F_{bx}} + C_{my} \frac{f_{by}}{(1 - \frac{f_a}{F_{ey}}) F_{by}} \leq 1.0 \]

The Use Of The Maximum Peak Values Of \(f_a\), \(f_{bx}\) and \(f_{by}\) Produces An Inconsistent Design

Axial Members Are Under Designed Compared To Bi-Axial Bending Members

SOLUTION?

Use Design Checks As A Function Of Time
Determination Of Wind Forces As Function Of Time

\[ R(t) = \sum f_i g(t)_i \]

1. ANALYSIS AND FORMULAS
2. FIELD MEASUREMENTS
3. WIND TUNNEL TESTS
WIND FORCES ACTING ON BUILDINGS

**Principal Wind Direction**

**Cross Wind Direction**

\[ \alpha(t) \]
VERTICAL DISTRIBUTION OF WIND FORCES

$F(t)_i$
PERIODIC WIND LOADING

\[ T_p = 10 \text{ TO } 50 \text{ Seconds} \]
Conversion Of Transient Solution To Periodic Solution

\[ y(t) = \text{zero initial conditions using piece-wise exact integration} \]

\[ x(t) = \text{unknown initial conditions} \]

\[ z(t) = y(t) + x(t) \quad \text{exact periodic solution} \]
PARALLEL ENGINEERING

AND

PARALLEL COMPUTERS
ONE PROCESSOR ASSIGNED TO EACH JOINT

ONE PROCESSOR ASSIGNED TO EACH MEMBER
PARALLEL STRUCTURAL ANALYSIS

DIVIDE STRUCTURE INTO "N" DOMAINS

FORM ELEMENT STIFFNESS IN PARALLEL FOR "N" SUBSTRUCTURES

FORM AND SOLVE EQUILIBRIUM EQ.

EVALUATE ELEMENT FORCES IN PARALLEL IN "N" SUBSTRUCTURES

NONLINEAR LOOP

TYPICAL COMPUTER
FINAL REMARKS

1. LINEAR AND NONLINEAR DYNAMIC ANALYSES CAN BE CONDUCTED, OF LARGE STRUCTURES, USING INEXPENSIVE PERSONAL COMPUTERS

2. SUBSTRUCTURE METHODS HAS MANY ADVANTAGES FOR LARGE STRUCTURES

3. TIME-HISTORY DYNAMIC WIND ANALYSES CAN NOW BE CONDUCTED OF STRUCTURES

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