CSMIP INSTRUMENTED BUILDING RESPONSE ANALYSIS AND 3-D VISUALIZATION SYSTEM (CSMIP-3DV)

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Abstarct

The CSMIP-3DV software system illustrates more than ever that seismic instrumentation of buildings is vital for learning from performance of buildings during earthquakes, enhancing engineering practice, and further development of seismic code provisions. The state-of-the-art features of CSMIP-3DV, for the first time, make it possible to evaluate seismic performance of dozens of buildings over many earthquakes in a systematic, consistent, and user-friendly manner. It is anticipated that by the end of the year 2004 CSMIP-3DV users will be able to investigate more than 80 instrumented buildings. Soon thereafter, the entire collection of more than 180 instrumented buildings will be implemented in CSMIP-3DV.

Introduction

This paper provides an overview of a new development sponsored by the California Strong Motion Instrumentation Program (CSMIP) that significantly enhances access to and the utility of strong-motion data obtained from instrumented buildings in learning seismic performance of buildings. Currently more than 180 buildings have been instrumented throughout California by CSMIP. Eventually information regarding all these buildings will be implemented in this system and made available to the structural engineering community. In the first phase of implementation anticipated to be completed before the end of 2004 about 80 buildings with significant earthquake records will be incorporated in this system. The system is scheduled to be released during the CSMIP-2004 Seminar in May 2004 with an initial implementation of about 30 buildings.

The system, code named CSMIP-3DV, permits visualization of building response to earthquake ground motions, facilities for adding newly instrumented buildings and downloading recently recorded building response data from the CISN Engineering Data Center website, and extensive facilities for analysis and evaluation of building response parameters such as displacements, story drifts, changes in dynamic characteristics of the building and so forth.

Following each earthquake, three-dimensional building response can be viewed within a short period of time on the CISN Engineering Data Center website. In addition, structural engineers will be able to download the datasets and perform their own investigations using the software system CSMIP-3DV installed on their own personal computers. The goal of this system is to revolutionize the use of strong-motion data obtained from instrumented buildings in structural engineering applications and improvement of seismic code provisions.

CSMIP-3DV Documentation

CSMIP-3DV is released on a CD-ROM disc and updated through the Internet. Three manuals document the CSMIP-3DV software system:

1. *CSMIP-3DV User Guide* contains necessary information for installation and basic use of the software system including techniques for downloading additional building datasets and software updates via the Internet.

2. *CSMIP-3DV Technical Manual* contains technical information on the methods utilized by CSMIP-3DV for calculation and analysis of instrumented building response during earthquakes. Details of interpolation techniques used, computations involved in producing three-dimensional visualization of building response, and methodologies utilized for interpretation of building vibration periods, mode shapes, and changes in the dynamic characteristics of the building during an earthquake, or from one earthquake to another, are contained in this manual.

3. *CSMIP-3DV Administrator's Manual* is made available to persons authorized to construct CSMIP-3DV models of instrumented buildings to expand the system's database of buildings and corresponding earthquake records. It contains instructions on using the system's building development utility for development of building models including associated earthquake-specific building and sensor information, maintenance of the CSMIP-3DV database, structure and hierarchy of building and earthquake information within the system, and management of the data and program updates on the CSMIP-3DV secure Internet server for download by end users.

Three-Dimensional Visualizations

CSMIP-3DV Building Models

CSMIP-3DV building models are not structural analysis models. They are models generated to provide a realistic view of response of buildings during earthquakes. All motions displayed by CSMIP-3DV building models are derived from active building instrumentation (sensor time histories). Therefore, although CSMIP-3DV does perform a variety of interpolations to estimate displacements of floors in between instrumented floors, it does not perform any structural analysis.

CSMIP-3DV building models consist of several components. Some of these components are mandatory and must be present in all models. Examples of mandatory components include story heights, sensor locations, floor slabs and grid points defining them. Other components are optional and are used to enhance visualization of the building. Examples of such components include columns, walls, braces, and façades. Inclusion of too many of the optional components in modeling of a large and complex structure may overburden the PC memory requirements and result in a time consuming pre-visualization calculation process.

Realistic visualization of complex structures may be obtained by careful modeling of floor slabs and inclusion of a proper façade texture. Selecting a proper texture for the exterior façade and enough grid points in laying out the floor slabs probably has the most impact on the user's perception of the building's visualization. For example, consider the Los Angeles – 54 story office building. Figure 1 shows the CSMIP information sheet for this building. The CSMIP-3DV model showing slabs and columns is presented in Figure 2. Although this figure is accurate, it is certainly not eye pleasing as it does not resemble an actual picture of the building shown in Figure 3. Figure 4 shows visualizations using several different exterior textures ending with the texture selected for visualization of the building.

Visualization Engine

CSMIP-3DV uses the Direct-3D component of Microsoft Direct-X animation engine for visualization of buildings. Direct-X is a very powerful graphics engine intended for development of video games on personal computers. It is commonly referred to as the gaming engine for the Microsoft Windows platform. The position (E-W, N-S and rotation) of the center of geometry of each floor for each time step during the response of the building to earthquake ground motion is calculated by the program. This position information along with story heights and plan boundaries of each floor is communicated to the Direct-3D engine which takes care of the necessary transformations and returning the position of every point on the building at each time step, as needed for visualization.

In CSMIP-3DV visualization, x is the horizontal axis at the bottom of the PC monitor screen, y is the vertical axis in the plane of monitor, and z is the axis perpendicular to the monitor screen pointing towards the user. The following transformation matrices are used for visualization. Please note that the 4th item on each vector is the scale factor (usually set to unity).

Translation:

$$[x_{new} \quad y_{new} \quad z_{new} \quad 1] = [x_{old} \quad y_{old} \quad z_{old} \quad 1]\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \Delta_x & \Delta_y & \Delta_z & 1 \end{bmatrix}$$

Scaling:

$$[x_{new} \quad y_{new} \quad z_{new} \quad 1] = [x_{old} \quad y_{old} \quad z_{old} \quad 1]\begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

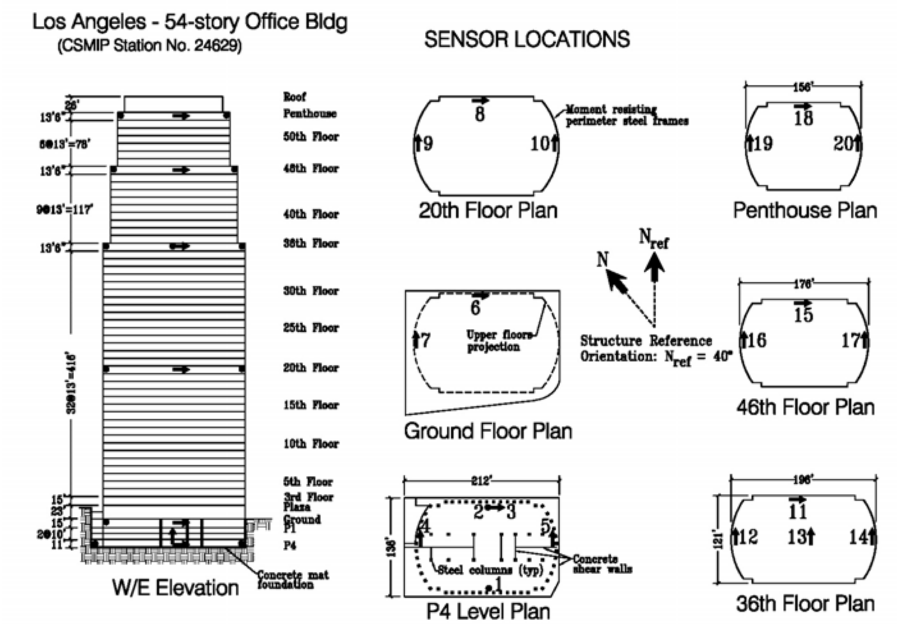


Figure 1. CSMIP data sheet for the Los Angeles 54 story Office Building

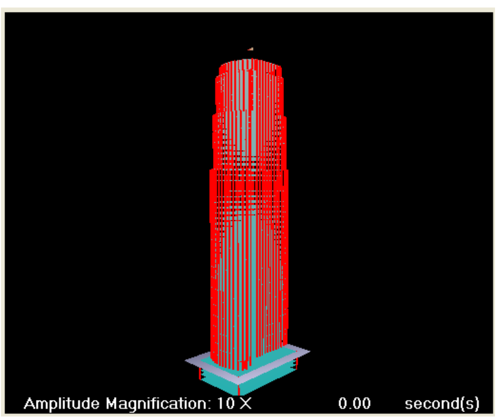


Figure 2. CSMIP-3DV model without the exterior façade

Figure 3. A photo of the Los Angeles – 54 story Office Building

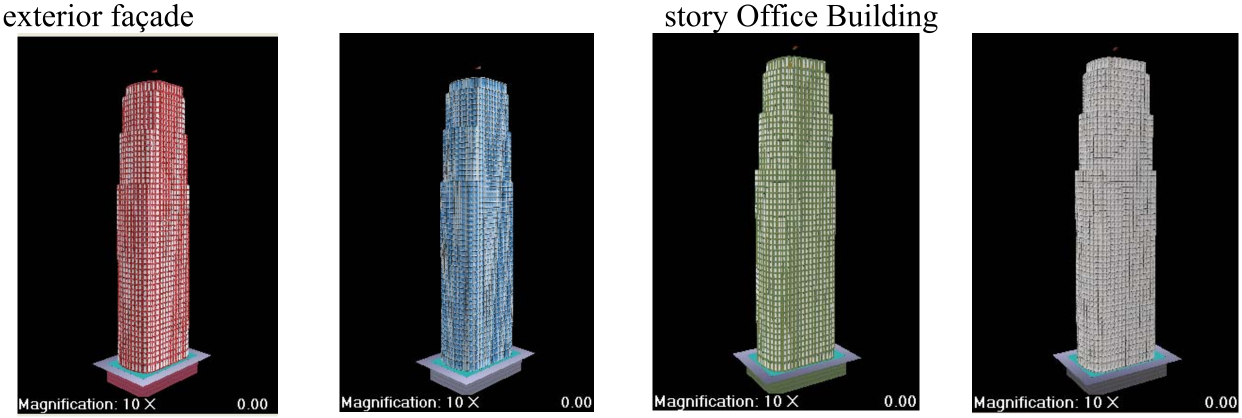


Figure 4. Some of the façade options examined for the Los Angeles 54 story Office Building

Rotation About *x* axis:

$$\begin{bmatrix} x_{new} & y_{new} & z_{new} & 1 \end{bmatrix} = \begin{bmatrix} x_{old} & y_{old} & z_{old} & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & Cos(\theta) & Sin(\theta) & 0 \\ 0 & -Sin(\theta) & Cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotation About *y* axis:

$$\begin{bmatrix} x_{new} & y_{new} & z_{new} & 1 \end{bmatrix} = \begin{bmatrix} x_{old} & y_{old} & z_{old} & 1 \end{bmatrix} \begin{bmatrix} Cos(\theta) & 0 & -Sin(\theta) & 0 \\ 0 & 1 & 0 & 0 \\ Sin(\theta) & 0 & Cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotation About *z* axis:

$$\begin{bmatrix} x_{new} & y_{new} & z_{new} & 1 \end{bmatrix} = \begin{bmatrix} x_{old} & y_{old} & z_{old} & 1 \end{bmatrix} \begin{bmatrix} Cos(\theta) & Sin(\theta) & 0 & 0 \\ -Sin(\theta) & Cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Interpolation Schemes and Virtual Sensors

Calculation of Story Displacements from Sensor Data

Calculation of story displacements is the first step for visualization and response evaluations. Instrumented buildings generally have sensors installed at a limited number of floors. Therefore, the displacements at floors in between the instrumented floors need to be approximated using appropriate interpolation schemes. Current version of CSMIP-3DV assumes that floor diaphragms are rigid in their own plane. The E-W and N-S displacements of each instrumented floor (A_x, A_y) and its rotation (θ) about a pre-defined point (usually the floor's geometric center) for each time step is calculated first. Then (A_x, A_y and θ) for floors in between are estimated using an interpolation scheme. Two interpolation schemes are currently implemented in CSMIP-3DV, linear and cubic spline. Both interpolation schemes may be combined as needed for a building as long as the range of floors they approximate do not overlap. For example, linear interpolation may be used for the sub-basement levels of a tall building followed by cubic spline interpolation for floors above the ground. The typical arrangement of sensors on an instrumented floor is shown in Figure 5.

This floor has three sensors with the coordinates (x_1, y_1), (x_2, y_2) and (x_3, y_3). For every time step these sensors report displacements A_1, A_2 and A_3. Let us assume that the floor's geometric center has coordinates (x_c, y_c). The relation between sensor displacements and those of a point with coordinates (x_c, y_c) on the floor is:

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & (x_1 - x_c) \\ 0 & 1 & (x_2 - x_c) \\ 1 & 0 & -(y_3 - y_c) \end{bmatrix} \begin{bmatrix} A_x \\ A_y \\ \theta \end{bmatrix}$$

The E-W and N-S displacements of a point with coordinates (x_c and y_c) on the floor may be obtained from:

$$u_x = A_x - (y_y - y_c)\,\theta$$
$$u_y = A_y - (x_x - x_c)\,\theta$$

The displacement of the geometric center of the floor is:

$$\begin{bmatrix} A_x \\ A_y \\ \theta \end{bmatrix} = \begin{bmatrix} \dfrac{y_c - y_3}{x_2 - x_1} & \dfrac{y_3 - y_c}{x_2 - x_1} & 1 \\ \dfrac{x_2 - x_c}{x_2 - x_1} & \dfrac{x_c - x_1}{x_2 - x_1} & 0 \\ -\dfrac{1}{x_2 - x_1} & \dfrac{1}{x_2 - x_1} & 0 \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix}$$

The same formulas may be used to obtain displacements of any other point on the floor by substituting the coordinates of that point instead of (x_c, y_c). Please note that for this method to work there must be three activated sensors per instrumented floor. If less than three sensors are present or activated per instrumented floor, then CSMIP-3DV's virtual sensor generation utility may be used to generate a time history for a virtual sensor at the desired location on the floor.

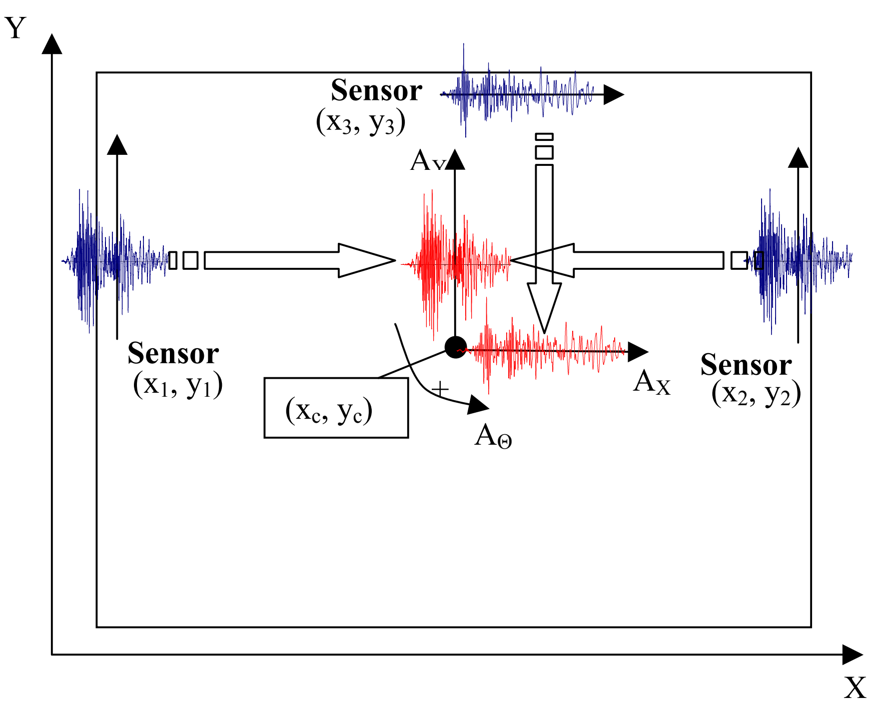


Figure 5. Typical sensor layout for an instrumented floor of a building

Interpolations

A cubic spline is a third-order curve applied to subsets of pre-defined *h* and *f(h)* values (i.e., sensor elevations and response parameters, respectively). Given a complete third order polynomial in the form:

$$f(h) = ah^3 + bh^2 + ch + d$$

the coefficients *a, b, c* and *d* are determined by forcing the *f(h)* values and their derivatives be equal at each node when calculated from adjacent sub-interval polynomials. The computation of spline coefficients for each-sub interval (the distance between two adjacent nodes) involves the solution of a tri-diagonal system of linear equations. Once the interval *i* containing the *h* value is determined, the value of the interpolated function is determined from

$$f_i(h) = a_i\left(h - h_i\right)^3 + b_i\left(h - h_i\right)^2 + c_i\left(h - h_i\right) + d_i$$

This operation is performed by CSMIP-3DV for every time step of the recorded sensor motion.

A cubic spline results in smooth transition between data points. This property is particularly desirable for conventional buildings but it is not suited for base isolated buildings. In such cases linear interpolations or linear-cubic spline combination may be used. Linear interpolation in CSMIP-3DV extends from one instrumented floor to the next. This means that the resulting displaced shape using linear interpolation will be piecewise linear if more than two instrumented floors are present in the building. Using the same notation used for cubic spline interpolation,

$$f\left(h\right) = ch + d$$

where the coefficients *c* and *d* are determined by forcing the *f(h)* value to be equal to the values of the instrumented floor at each end. Therefore,

$$f_i\left(h\right) = c_i\left(h - h_i\right) + d_i$$

Please note that CSMIP-3DV does not *extrapolate* displacements. That is sensors must be present at the base and the roof of the building.

Virtual Sensors

There are occasions where an instrumented floor has less than three sensors present or activated during an earthquake. Using the techniques described above, such floors would be excluded from analysis and valuable earthquake data from the sensors on such floors would not be taken into consideration. Examples of where the use of virtual sensors may be helpful are given in the Figures 6 and 7.

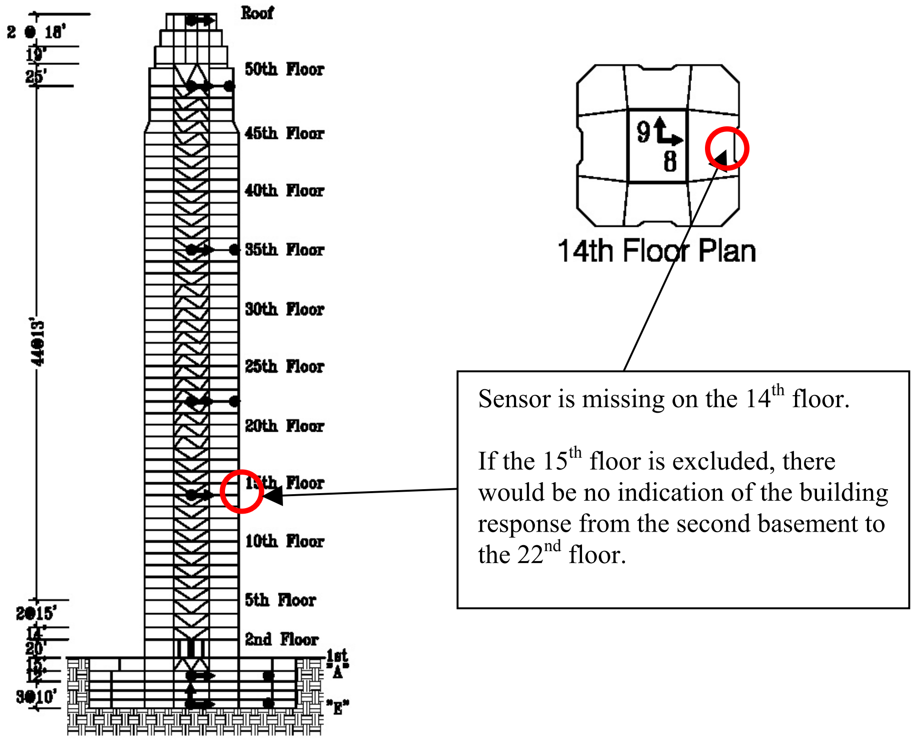


Figure 6. The need for virtual sensors (52 Story Los Angeles Building)

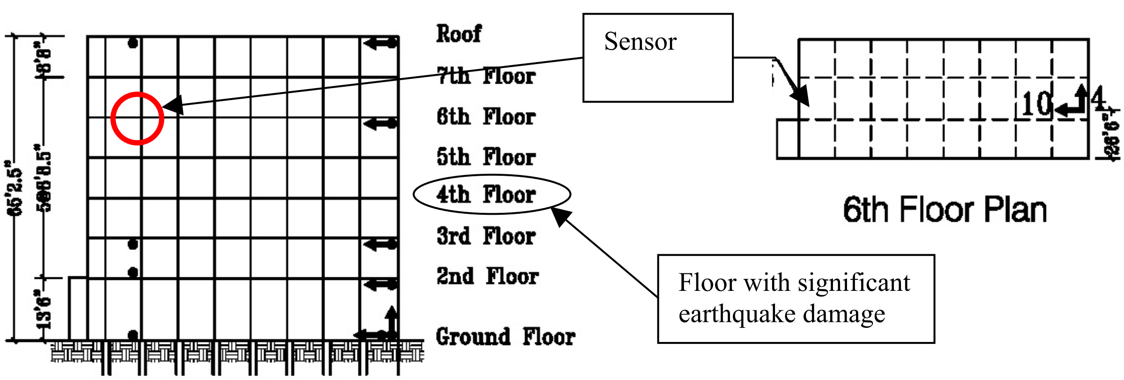


Figure 7. The need for virtual sensors (7 Story Van Nuys Hotel)

CSMIP-3DV generates virtual sensor time histories at the locations specified by the user as follows. First, interpolation according to the rules specified for the building is performed along the vertical line where a virtual sensor is located. Then a virtual sensor time history is generated and saved. Once the desired virtual sensor data files are generated, the problem is reduced to the routine interpolations that CSMIP-3DV performs. For example, in Figure 8 one instrumented floor has two real sensors (sensors 7 and 8). In order to define the virtual sensor's time history, CSMIP-3DV can use the time histories from sensors installed in that location on other floors (i.e. sensors 1, 4 and 9) to estimate the time history that a sensor at the desired location would have generated. Once the virtual sensor time history is created, the floor with the two real sensors could be used as an ordinary instrumented floor.

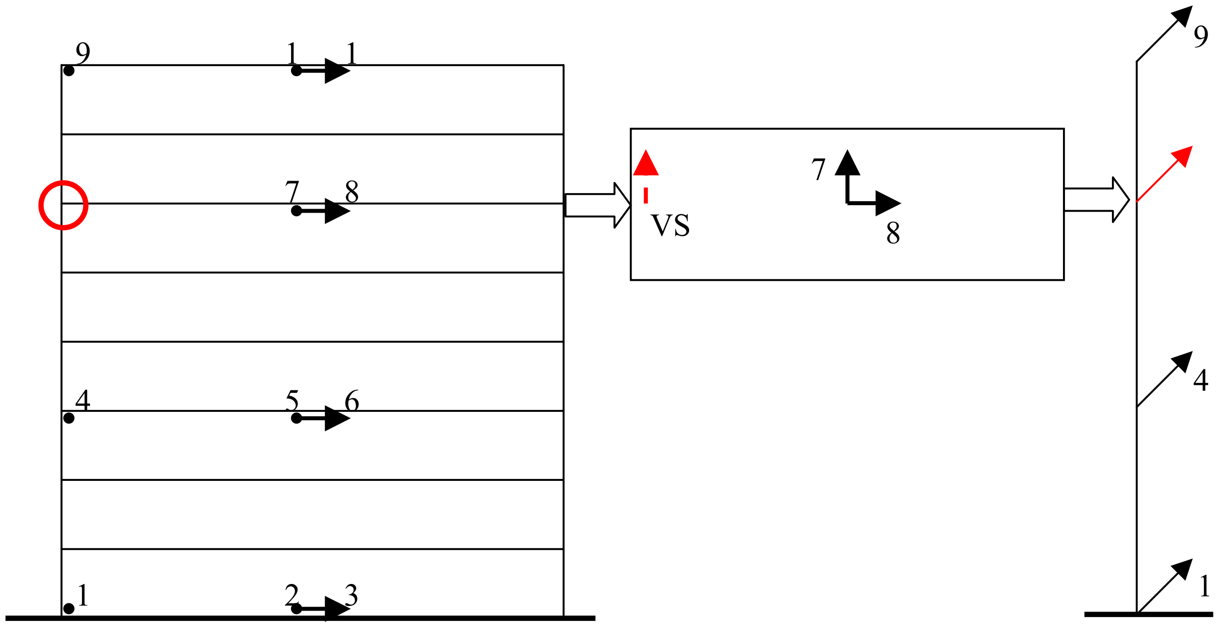


Figure 8. Example of virtual sensor generation

To verify the accuracy of this approach, we removed the real sensor data from selected floor of a number of buildings, generated virtual sensor time histories at the same positions and then compared the real and virtual time histories obtained for the same location. In all instances the virtual sensor was remarkably accurate in estimating the maximum displacements. It would deviate in some cases, however, from intermediate response values particularly in the high frequency portions of the time history. An example of such comparison is shown in Figure 9.

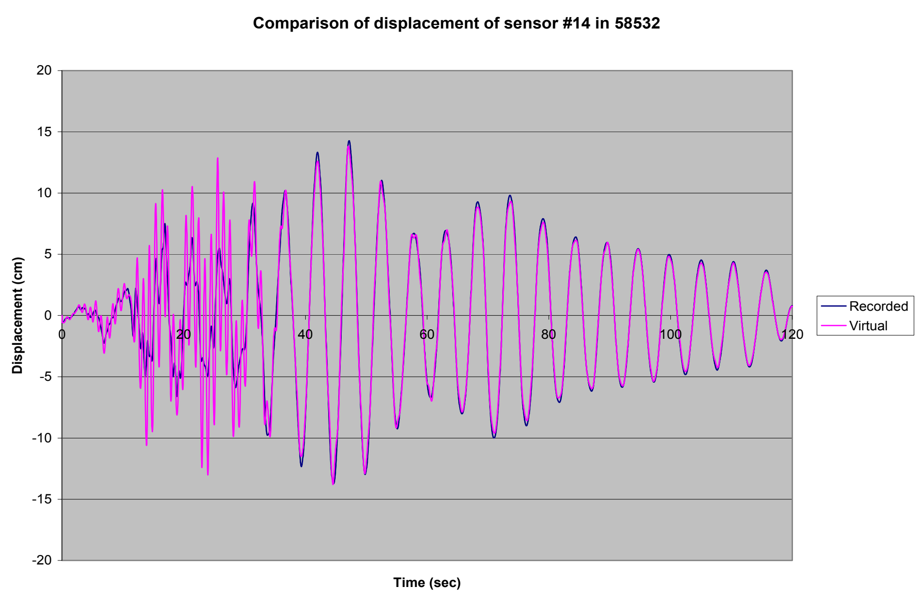


Figure 9. Comparison of an actual and the corresponding virtual sensor data

Evaluation and manipulation of Sensor Data

CSMIP-3DV offers a multitude of facilities for evaluation and manipulation of sensor data. As far as sensor time histories are concerned, up to four sensors may be selected at a time and their records added, subtracted, and averaged. For each sensor, acceleration, velocity and displacement records are available (see Figure 10). Response spectra facilities for evaluation of spectral displacement (SD), spectral velocity (SV), pseudo-velocity (PSV), spectral acceleration (SA), tripartite plot of response spectra, Fourier amplitude, PSA versus SD (ADRS), and SV and PSV on one graph. The user may select the desired level of damping. By default CSMIP-3DV displays the values corresponding to all damping levels (0%, 2%, 5%, 10%, and 20%).

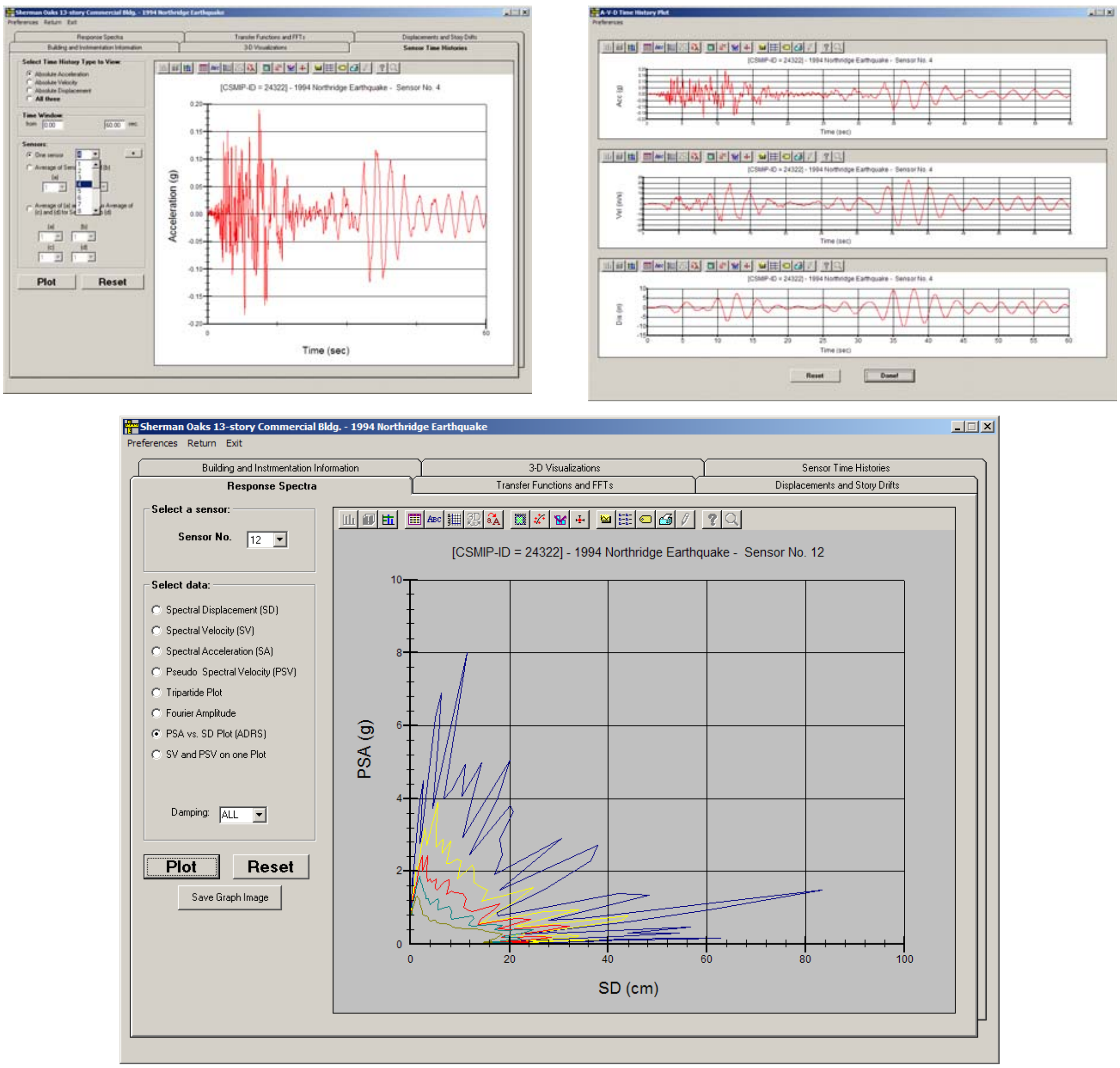


Figure 10. Examples of CSMIP-3DV sensor data manipulation utilities

Key Response Parameter Evaluations

CSMIP-3DV calculates lateral displacements and story drifts for various floors from the time history of sensors installed and instrumented floors of the building. Floors with sensors are identified by a ☒ on the graphs. A combination of cubic spline and linear interpolations are used to estimate the motion of the floors in between instrumented locations. For example, for a base-isolated building, there is a discontinuity in the function between the floors below the isolation plane and the ones above this plane. Therefore, CSMIP-3DV may use a linear interpolation for floors below the isolation plane and a cubic spline interpolation for floors above the isolation plane (see Figure 11). The type of various interpolations used and the limits of their application over the height of the building are set in one of the two input files prepared for the building.

The user may evaluate lateral displacements, inter-story drifts, or inter-story drift ratios. CSMIP-3DV also displays the envelope of negative and positive values of the parameter being investigated during the selected earthquake on the graph. The user may select any two adjacent floors to view a time-history of inter-story drifts or drift-ratios between these floors and time history of that parameter (Figure 12.

Each of these response parameter values may be evaluated in one of the two following directions:

- building's reference E-W direction, or
- building's reference N-S direction

Response parameter values may be examined at any of the following times:

- Any instant of time selected by the user.
- At the time of maximum E-W lateral displacement
- At the time of maximum N-S lateral displacement
- At the time of maximum E-W story drift throughout the building
- At the time of maximum N-S story drift throughout the building

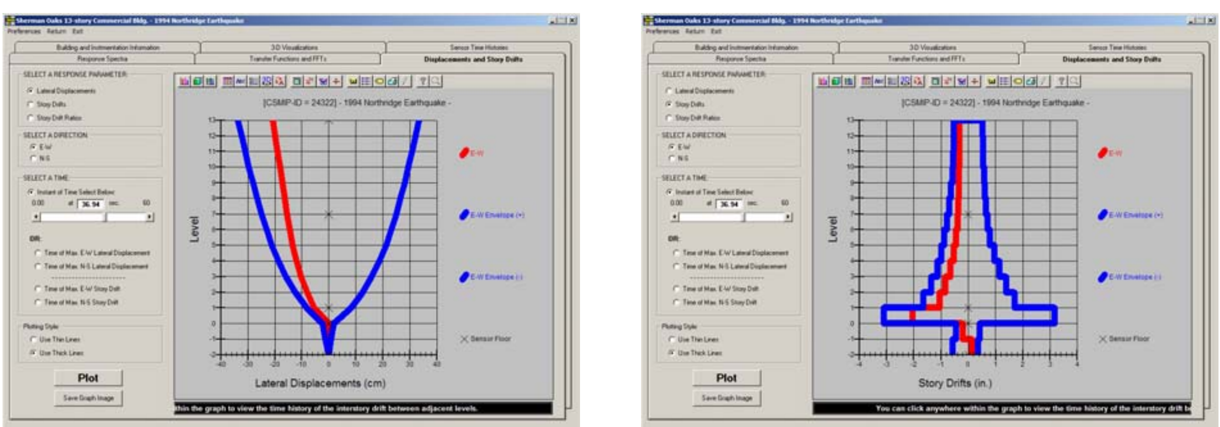


Figure 11. Examples of story displacement and drift diagrams generated by CSMIP-3DV

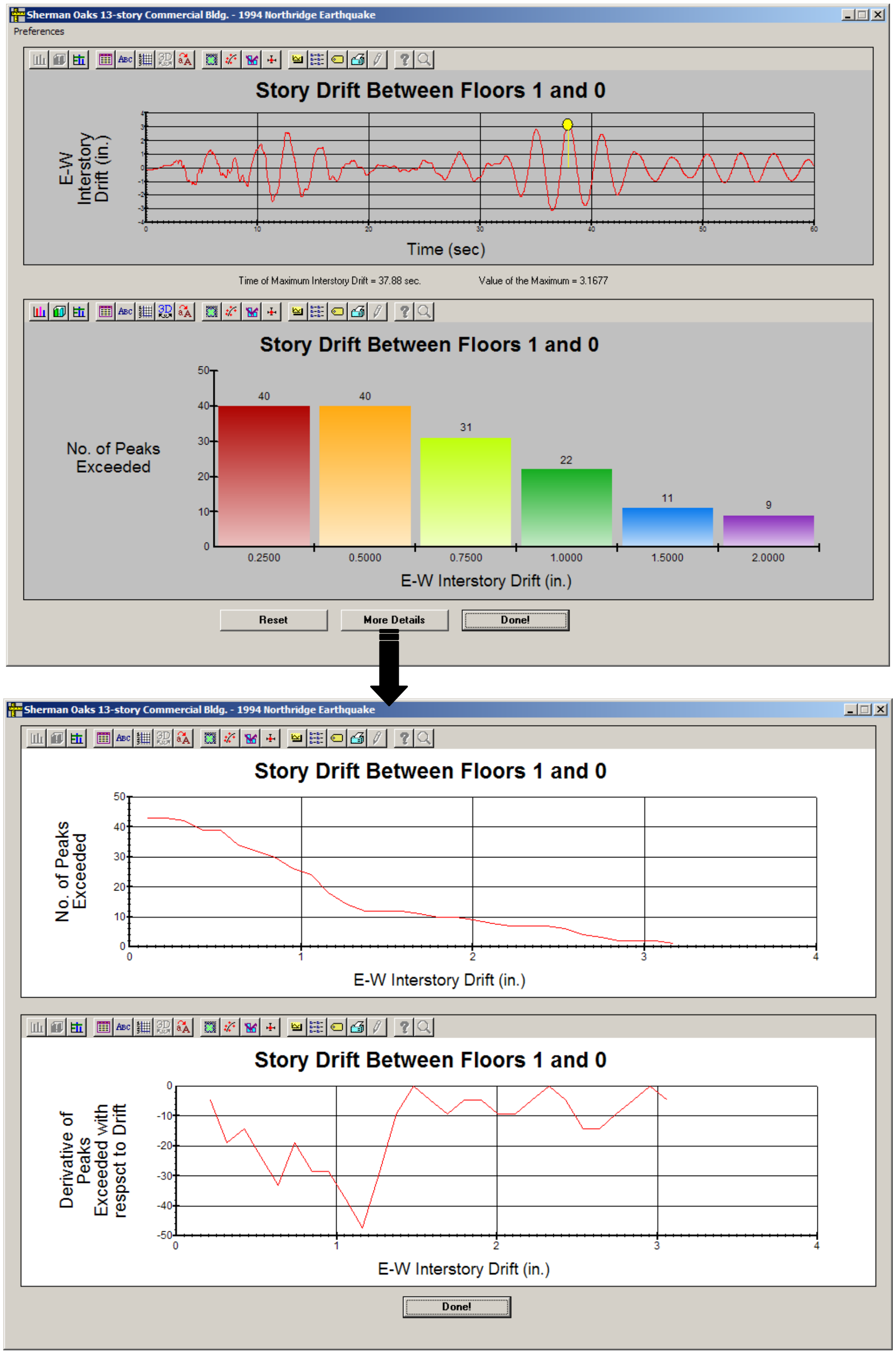


Figure 12. Evaluation of interstory drift time history and number of times that various thresholds of drift are exceeded.

Transfer Functions and Fast Fourier Transforms

Fourier Transforms

The CSMIP Instrumented Building Response Analysis system extracts the time histories and response spectra directly from appropriate SMIP Volume 2 and 3 data files. The program extracts, decompresses, utilizes, and discards on-the-fly the decompressed files it needs for any given operation. The transformation from the time domain to the frequency domain is based on the *Fourier Transform* defined as

$$S_x(f) = \int_{-\infty}^{\infty} x(t)\, e^{-i2\pi ft}\, dt$$

where *x(t)* is the time domain representation of the signal *x* (i.e., the sensor time history); $S_x(f)$ is the frequency domain representation of the signal *x* and $i = \sqrt{-1}$.

Since the sensor time histories are given at distinct intervals (i.e., 50 or 100 data points per second), numerical integration techniques need to be used

$$S_x(m\Delta f) = \int_{-\infty}^{\infty} x(t)\, e^{-i2\pi ft}\, dt$$

where $m = 0, \pm 1, \pm 2$ etc., Δf is the frequency spacing of the lines and Δt is the time interval between samples. As it is not possible to numerically evaluate this integral from minus to plus infinity, the transform is limited to a finite time interval and hence we can rewrite the above formula as

$$S_x(m\Delta f) = \Delta t \sum_{n=0}^{N-1} x(n\Delta t)\, e^{-i2\pi m\Delta fn\Delta t}$$

or as the *Discrete Fourier Transform (DFT)*:

$$S_x^{'}(m\Delta f) = \frac{T}{N} \sum_{n=0}^{N-1} x(n\Delta t)\, e^{-i2\pi mn/N}$$

Fast Fourier Transforms

As the summation of the series used in the discrete Fourier transform (DFT) is computationally time intensive, a more efficient method called the *Fast Fourier Transforms* (FFT) is normally used. CSMIP-3DV uses the *Danielson-Lanczos* or *bit reversal* technique for computing the FFT of time series. FFT algorithms, however, this method requires the number of data points (*N*) be a multiple of 2. The program automatically computes the intervals of time that meet this requirement. The user can select the portion of the record to use in computing the Fourier Transform.

Various choices are provided for computing the Fourier Transform:

1. Compute the Fourier Transform of a single sensor record.
2. Compute a Transfer Function between two sensor records. A transfer function is defined as the complex ratio of the Fourier Transform of two sensor records.

3. Compute the product of the Fourier Transform of two sensor records. Note, the result is a complex number.
4. A transfer function using four sensor records, with either the difference or sum of two sensor records in the denominator or numerator. The difference or sum of the sensors is done in the time domain before the Fourier transform is computed.

All the above options can be used using the acceleration, velocity or displacement data for each sensor. All computations are done in double precision.

Windowing Functions

Windowing functions are used to reduce leakage. Leakage is a problem which is a direct consequence of the need to take only a finite length of time history coupled with the assumption of periodicity. The Fourier Transform of a sinusoidal time trace with a finite length that is not an integer multiple of its period, will not indicate the single frequency which the original time signal possessed. Energy is 'leaked' into a number of the spectral lines close to the true frequency and the spectrum is spread over several line or windows.

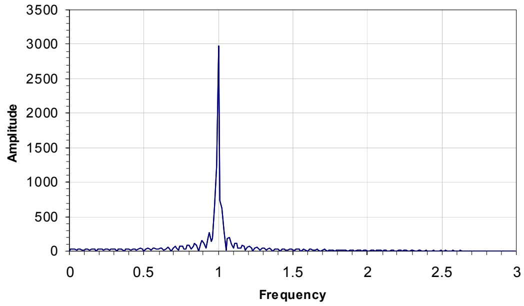
One practical solution to the leakage problem is the use of windowing functions. There are many different windowing functions available for different classes of problems. Windowing involves the imposition of a prescribed profile on the time signal prior to performance of the Fourier Transformation. The analyzed signal is given as

$$x'(t) = x(t) \cdot W(t)$$

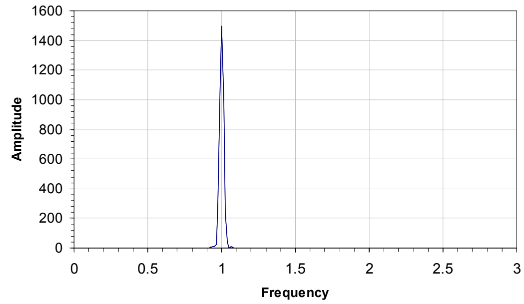
where *x(t)* is the original time trace and *W(t)* is the windowing function.

A number of windowing functions have been implemented in CSMIP-3DV. Figure 13 shows Fourier transform of a sine wave (f = 1 Hz) with various windowing functions.

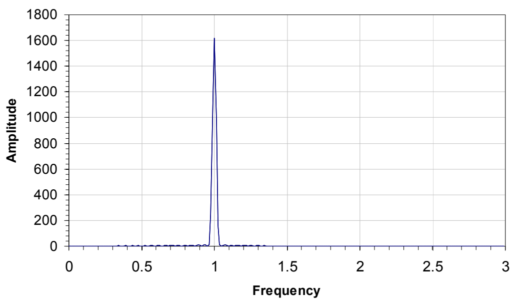
1. Hanning Windowing Function:
$$W(n) = 0.5 - 0.5\cos(2\pi n / N)$$
2. Hamming Windowing Function:
$$W(n) = 0.54 - 0.56\cos(2\pi n / N)$$
3. Blackman-Harris Windowing Function:
$$W(n) = a_0 - a_1\cos(2\pi n / N) + a_2\cos(4\pi n / N) - a_3\cos(6\pi n / N)$$
where $a_0 = 0.355768$, $a_1 = 0.487396$, $a_2 = 0.144232$ and $a_3 = 0.012604$.
4. Cosine Taper Window:
$$W(n) = 0.5 - 0.5\cos(2\pi n /(N/4)) \qquad \text{for } n = 1 \ldots N/4$$
$$W(n) = 1 \qquad \text{for } n = N/4 \ldots 3N/4$$
$$W(n) = 0.5 - 0.5\cos(2\pi(n - 3N/4)/(N/4)) \qquad \text{for } n = 3N/4 \ldots N$$



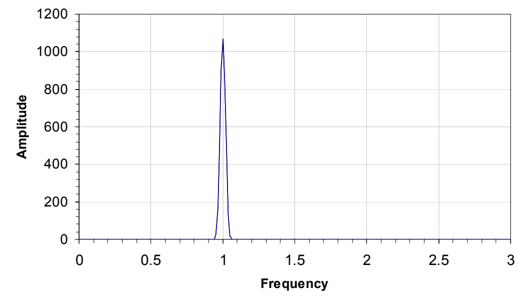
(a) no windowing function



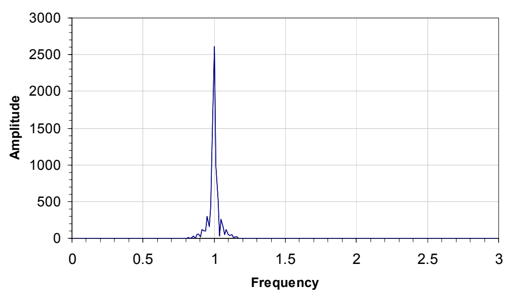
(b) Hanning windowing function



(c) Hamming windowing function



(d) Blackman-Harris windowing function

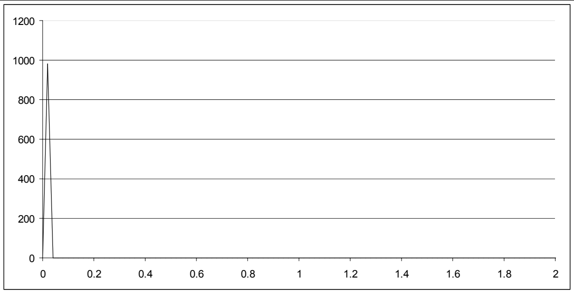


(e) Cosine-Taper windowing function

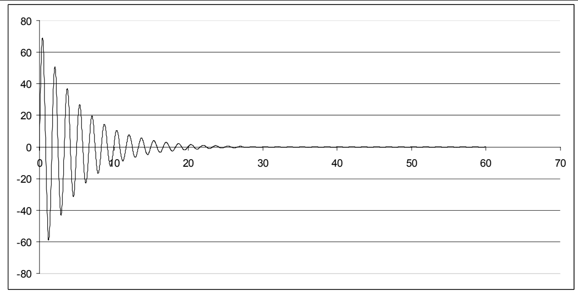
Figure 13. Fourier transform of a sine wave (f = 1 Hz) with various windowing functions

Transfer Functions

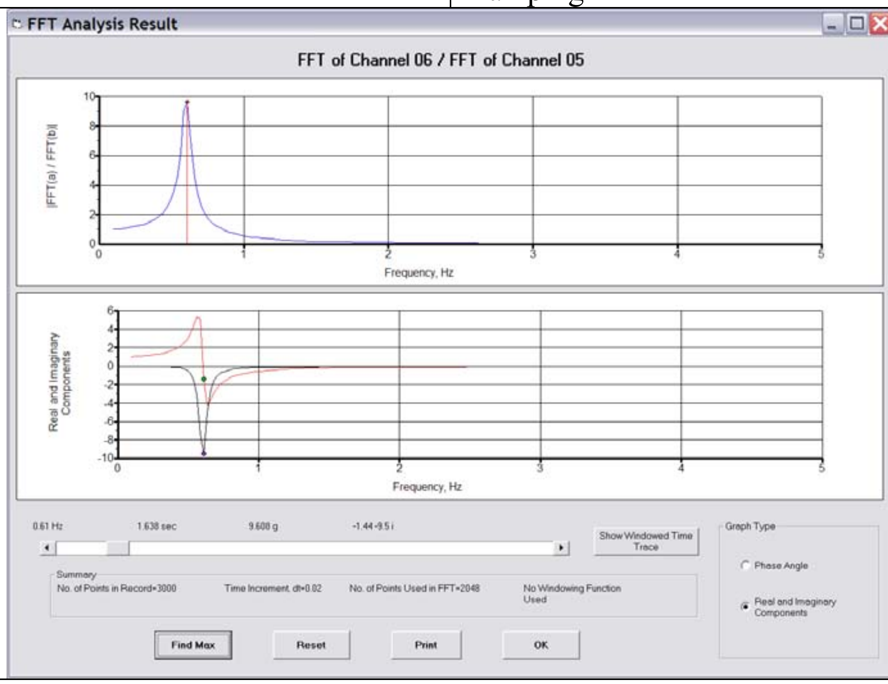
For a single degree of freedom system, the Transfer Function is defined as the frequency domain response due to an impulse function. The input impulse function for a single degree of freedom system is shown is Figure 14a. The response of the SDOF system, which has a natural period of 1.7 sec. is shown in Figure 14b. The Transfer Function obtained for this SDOF system using the CSMIP-3DV is shown in Figure 14c. The Transfer Function obtained is as is theoretically predicted with the real component changing signs and the imaginary component showing a peak at the natural frequency.



(a) Input impulse function



(b) Response of a SDOF system with a fundamental period of 1.7 sec. and 5% Damping



(c) CSMIP-3DV generated transfer function showing the real and imaginary components

Figure 14. Transfer function for a single degree of freedom system

Examples of the transfer functions for CSMIP Station No. 24629 (Los Angeles 54 Story Office Building) in response to the 1994 Northridge earthquake are presented here. A transfer function of Sensor No. 19 relative to a sensor in the basement (FFT for Sensor 19/FFT for Sensor 4) clearly indicates that the first transverse mode of the building has a period of 6.3 secs. The real component changes sign at this period (Figure 15) as would be expected at a mode of vibration for the building.

It is possible to remove the effect of torsional modes by using the average of the sensors at a floor. An example of a transfer function using the average of sensor records at the roof and the basement is shown in Figure 16. Using the difference of the sensor records, it is also possible to show only the torsional modes. An example is shown in Figure 17 using the sensor records at the roof and basement. The first torsional mode occurs at 2.78 Hz.

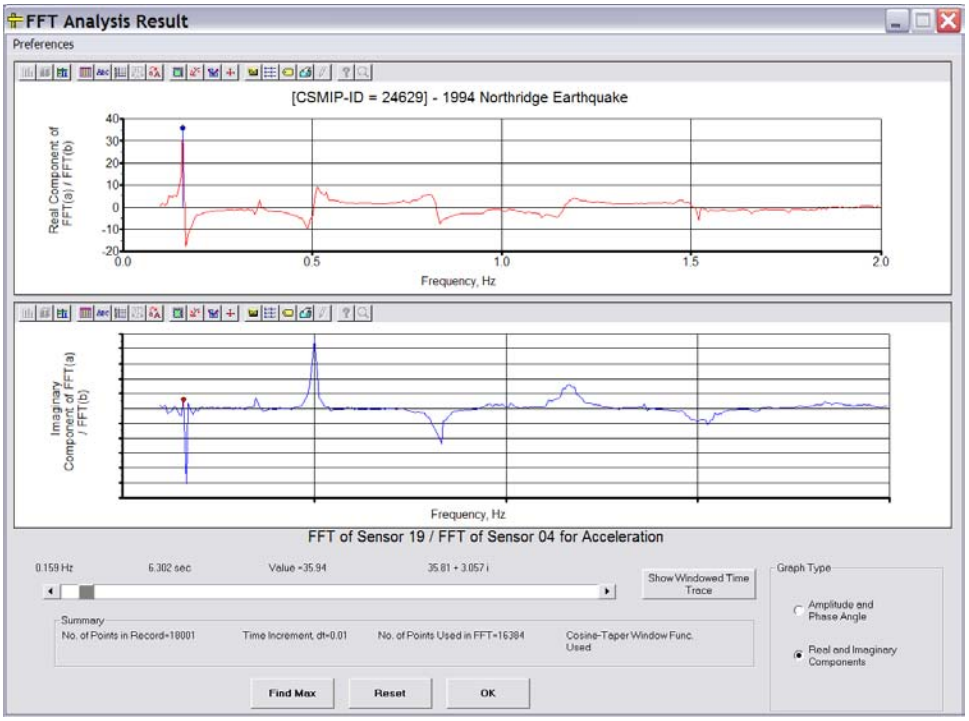


Figure 15. Real and imaginary components of transverse (north-south) transfer function of roof relative to the ground

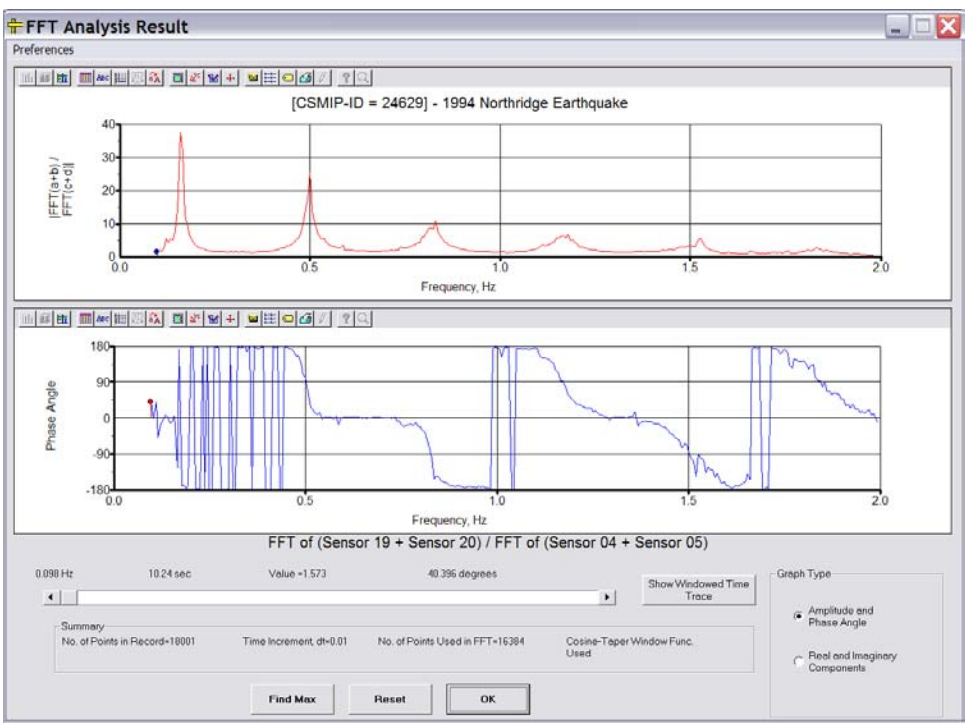


Figure 16. Transfer function of roof relative to basement without torsion

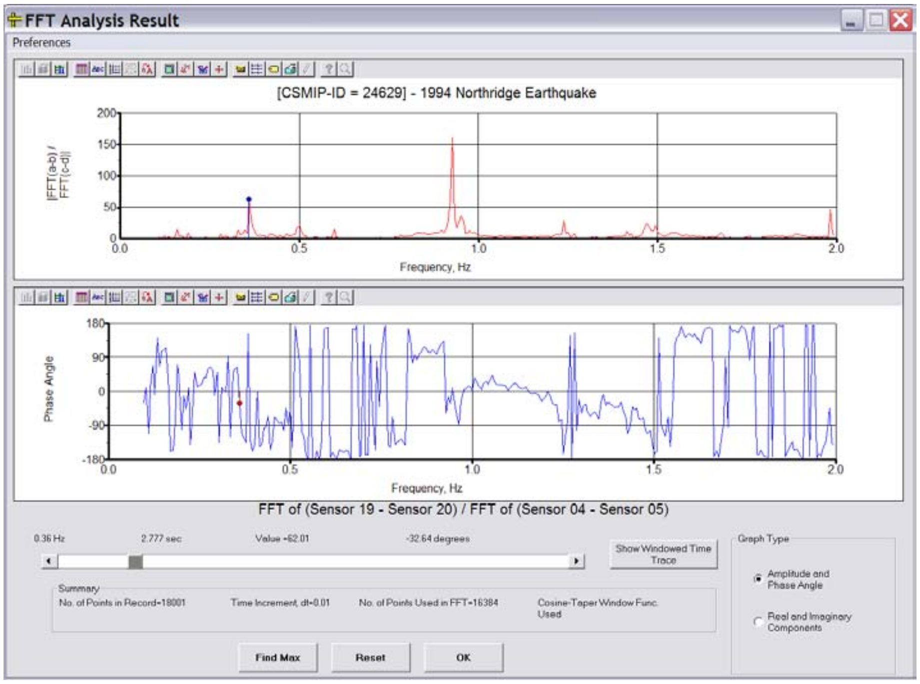


Figure 17. Torsional transfer function of roof relative to basement

Moving Windows FFT in Instrumented Buildings

CSMIP-3DV has an option to perform a moving windows FFT analysis. Here the FFT analysis is done for a finite time window (t_{slice}), the window is offset by t_{shift} seconds and the FFT analysis is repeated. The Fourier transform this obtained is then plotted as a three-dimensional surface with the frequency as the x-axis, the start time of the slice as the y-axis and the amplitude as the z-axis. Such a Moving Windows FFT plot can show the relative amplitudes of vibrations in the various modes of the building as the earthquake progresses. It can also show if the frequency of vibration in any mode changes during an earthquake. However, such an analysis is very sensitive to the parameters used such as t_{slice}, t_{shift}, sampling time and the number of points used to compute the FFT. An example is shown in Figure 18 for sensor 19 for CSMIP Station No. 24639 (54-story office building located in downtown Los Angeles). The graph on the left shows the three-dimensional surface obtained while the graph on the right shows slices of the surface at selected start times or frequencies. The amplitude of the various modes decrease as the earthquake progress, as would be expected. The frequency of the various modes do not appear to change as would be expected for a building that showed no signs of damage during the 1994 Northridge Earthquake.

An example of a building where the frequency of the fundamental mode changed during an earthquake is CSMIP station 24580, the Los Angeles Fire Command Center. The moving windows FFT analysis of Sensor No. 15, located on the roof of the building, is shown in Figure 19. The analysis shows the dominant frequency of vibration of the building changes to a lower frequency as the earthquake progresses. It should be noted as the window of data used for the FFT has a finite length and therefore instantaneous changes in frequencies show up a gradual shift of the larger amplitude to a lower frequency.

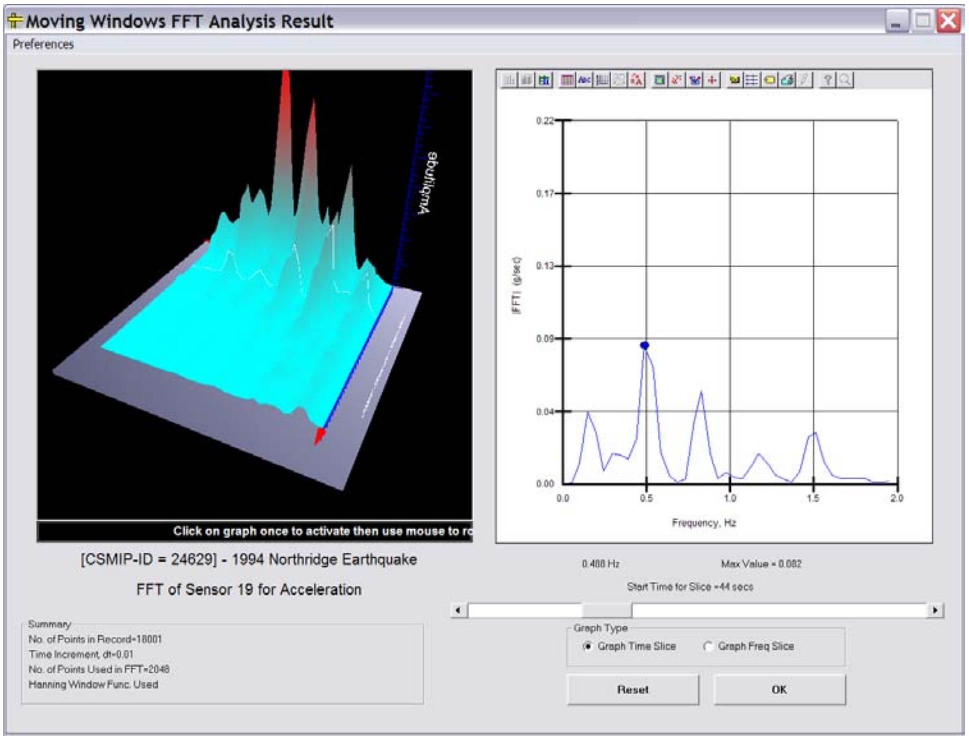


Figure 18. Moving windows FFT analysis of 54-story office tower

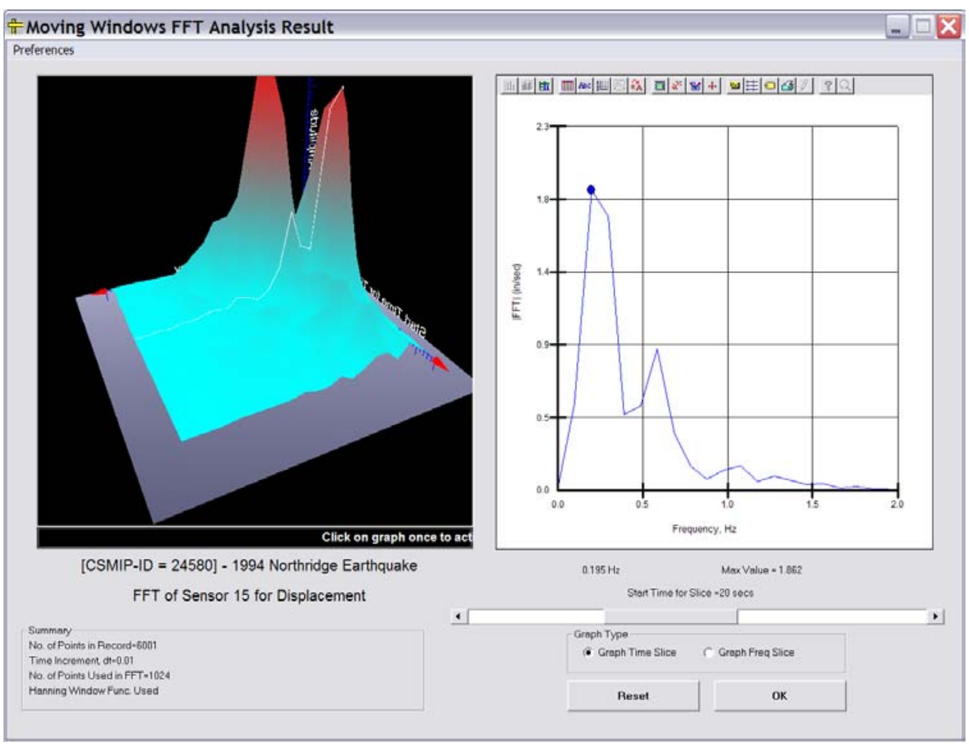


Figure 19. Moving windows FFT analysis of Los Angeles Fire Command Center

Conclusion

CSMIP-3DV permits visualization of building response to earthquake ground motions, facilities for adding newly instrumented buildings and downloading recently recorded building response data from the CISN Engineering Data Center website, and extensive facilities for analysis and evaluation of building response parameters such as displacements, story drifts, changes in dynamic characteristics of the building and so forth. Following each earthquake, three-dimensional building response can be viewed within a short period of time on the CISN Engineering Data Center website. In addition, structural engineers will be able to download the datasets and perform their own investigations using the software system CSMIP-3DV installed on their own personal computers. The goal of this system is to revolutionize the use of strong-motion data obtained from instrumented buildings in structural engineering applications and improvement of seismic code provisions.

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