

EvW (Earthquake versus Wind) Application

1. Tool Audience (Users):

- 1) Students taking courses in structural dynamics, earthquake or wind engineering.
- 2) Researchers/Practitioners trying to understand a building response to a Natural Hazard.

2. Tool Purpose:

This educational application will allow the user to explore the differing effects of Wind and Earthquake loads on a building. The application will also allow them to study the effects of different building parameters, such as mass, stiffness, and yield force.

The building itself is to be represented by a shear building model: an idealization of a structure in which the mass is lumped at the floor levels and the beams are assumed infinitely stiff in flexure and axially inextensible, and the columns are axially inextensible. The user will input the floor weights and story properties (stiffness, yield strength, hardening ratio) of the stories, and a damping ratio for the elastic modes of vibration.

The user will quickly be able to explore the effect of changing weight, height, and stiffness on the time history response. In addition, nonlinear effects due to P-Delta effects and soft story mechanisms will also be able to be studied.

For the earthquake loading, the equations of motions are set up using the uniform excitation approach, i.e. $MA + CV + KU = -MAg$ where A_g is the ground acceleration.

For the Wind loading, the equations of motions are expressed as $MA + CV + KU = F$ where F is the dynamic wind force caused by the fluctuating winds. The Kaimal wind spectrum and the Davenport coherence function are employed to describe correlated wind fields in the frequency domain. With these models, fluctuating wind velocities at each floor level are simulated in terms of the discrete frequency function scheme (Wittig and Sinha 1975), which is adopted due to its simplicity and fast computation. The dynamic wind forces are then determined by the simulated fluctuating winds.

4. User Workflow:

The main window of the running application can be broken into two panels: the input on the left and the output on the right, as shown below in Figure 1.

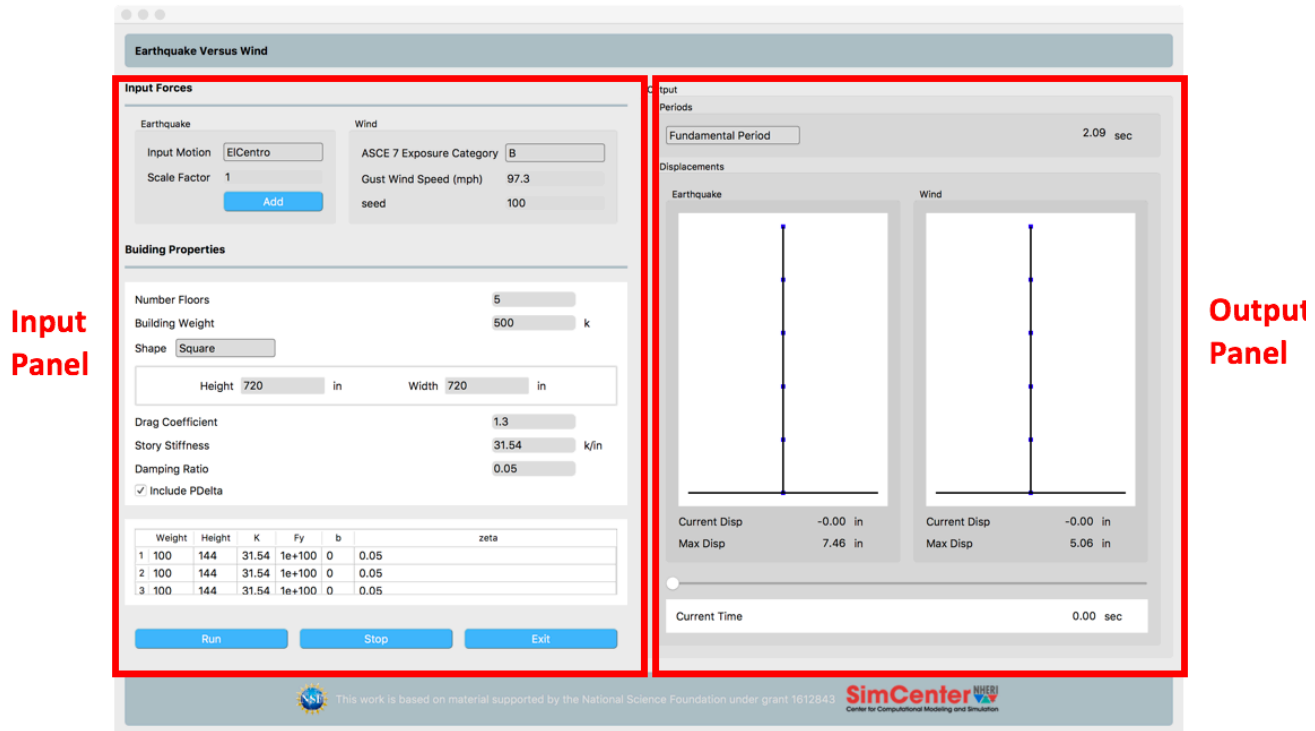


Figure 1: Display of Running Tool showing Input and Output Panels

A high level description of user workflow, would be user starting the tool and, until the user exits, they would interact with the input panel to update earthquake motion, wind loading, and building properties and instantly view the changes these modifications make in the output panel. The user would go back to input panel and make subsequent changes to see the effect on response of these changes. At any-time before exiting the tool, the user will have the option to save the current settings or load a saved file of previous settings.

5. System Specification:

As shown in Figure 2, the input panel is itself broken into 5 panels:

The input panel is divided into five sections, each highlighted with a red border and a red label:

- Earthquake Motion:** Contains a dropdown menu for 'Input Motion' (set to 'ElCentro'), a 'Scale Factor' input (set to 1), and an 'Add' button.
- Wind Characteristics:** Contains a dropdown menu for 'ASCE 7 Exposure Category' (set to 'B'), a 'Gust Wind Speed (mph)' input (set to 97.3), and a 'seed' input (set to 100).
- Global Building Properties:** Contains inputs for 'Number Floors' (5), 'Building Weight' (500 k), 'Shape' (Square), 'Height' (720 in), 'Width' (720 in), 'Drag Coefficient' (1.3), 'Story Stiffness' (31.54 k/in), 'Damping Ratio' (0.05), and a checked 'Include PDelta' checkbox.
- Individual Floor/Story Properties:** A table with columns: Weight, Height, K, Fy, b, and zeta. It contains three rows of data for floors 1, 2, and 3.
- Push Buttons:** Contains three buttons: 'Run', 'Stop', and 'Exit'.

	Weight	Height	K	Fy	b	zeta
1	100	144	31.54	1e+100	0	0.05
2	100	144	31.54	1e+100	0	0.05
3	100	144	31.54	1e+100	0	0.05

Figure 2. Input Panel

- Earthquake Motion:** for defining the earthquake input motion. Here the user can from a drop down menu select the earthquake motion and scale the motion as desired. Additional motions can be entered from the file system by selecting the add button. These motions must be in a specific format and units must be in g. Once added, the motion can be selected from the drop-down menu.
- Wind Characteristics:** for defining the exposure category, wind speed and a random seed. The determination of wind forces is, as described in the theory, based on a
- General Building Properties:** an area for the user to enter general properties, such as shape and overall dimensions, building height, story stiffnesses, building drag coefficient. Also included in this section is a flag indicating whether the user wants P-Delta forces to be included in determination of the response and a field for entering the damping ratio.
- Individual Floor/Story Properties:** The overall properties sets the properties for all floors and stories. Once set, individual floor and story values can be set in this spreadsheet area.

- e) Push Buttons: a set of push buttons: The run is used to start display of the building displacement response in the output panel, the stop button stops it. The exit button is used to exit the program.,

The output panel, as shown in Figure 3, is broken into 4 panels:



Figure 3: Output Panel

- Structure Periods: A panel in which the user selects the period of interest from a drop-down menu and that period is displayed on the right side of the panel.
- Earthquake Displacement Response: Displays for the current time the displaced shape of the building, the current roof displacement and the max roof displacement,
- Wind Displacement Response: Does the same as above for the response of the building to the wind event.
- Slider Bar: for manually moving the current time
- Current Time: a visual display of the current time

Note: The entire motion can be displayed by pushing the run button at the bottom of the input panel.

Additional viewing options are available from the applications main windows view menu (location depends on operating system). This is a drop-down menu allowing user to select from any of the following view:

- a) Floor Displacement versus Time
- b) Story Force versus Time
- c) Story Force versus Story Displacement
- d) Applied Floor Force versus Time.

As shown in Figure 4 of Story Forces versus time, each view provides a panel for user to select the floor or story of interest. User enters the desired floor or story number in the text entry field. Two panels below the selection show the results individually, the top for the Earthquake Response and the bottom for the Wind Response.

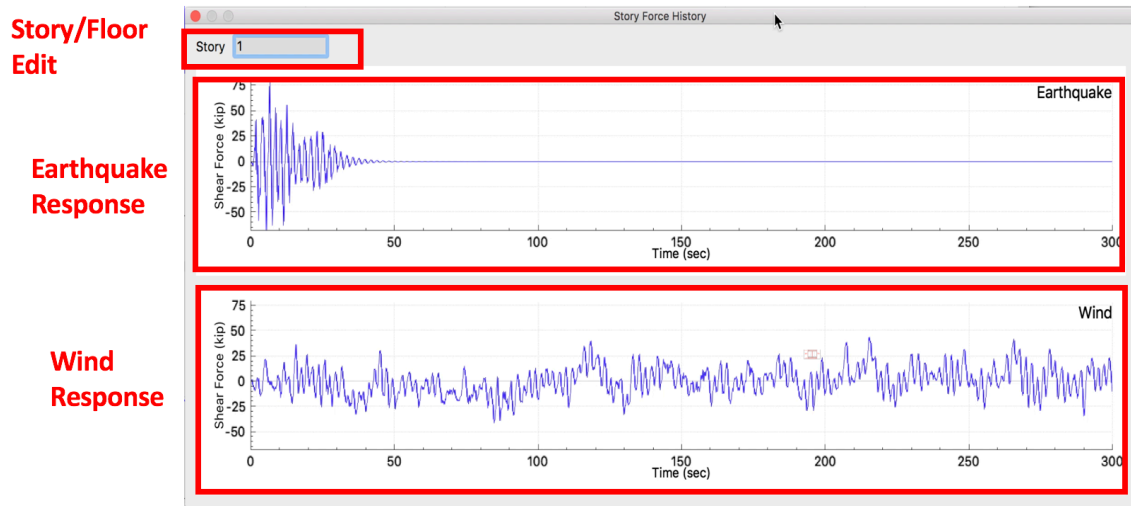


Figure 4: Story Forces Versus Time View

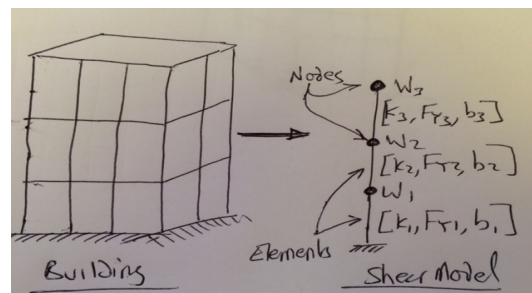
10. Source Code:

This source code for the tool is released under the 2-clause BSD License, commonly called the FreeBSD license. It is available for download from the tools GitHub repository: <https://github.com/NHERI-SimCenter/EVW>

12. Verification and Validation:

12.1 Theory:

A simplified model of a building is obtained by assuming that all the building weight is lumped at the floor levels, that the floor beams are rigid, and columns are axially inextensible. Together these assumptions allow us to generate a “shear-beam” or stick model of the building.



The model consists of a set of nodal points, one at each floor level, and a set of interconnecting elements representing the columns. The model is fully described by the floor weights, W_i , at the nodal points and by the element properties [K_i , F_{Yi} and b_i]: where K_i is the sum of the column stiffnesses, F_{Yi} the yield strength of the story, and b the kinematic hardening ratio. At any time t the equation of motion is:

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{F}_s(\mathbf{u}(t)) = \mathbf{P}(t)$$

A transient analysis of the structure now simply involves satisfying the equilibrium equation at the nodal points. A numerical approach solves the equations at a number of discrete time intervals, $t = i * \Delta t$, apart:

$$\mathbf{M}\ddot{\mathbf{u}}_i + \mathbf{C}\dot{\mathbf{u}}_i + \mathbf{F}_s(\mathbf{u}_i) = \mathbf{P}_i$$

For solving the equations the application uses the implicit Newmark constant average acceleration scheme. A consequence of this is that the nodal responses for time $t + \Delta t$ are determined using equilibrium at the same time step. The Newmark scheme provides difference relations that allow the velocities $\dot{\mathbf{u}}_{i+1}$ and accelerations $\ddot{\mathbf{u}}_{i+1}$ to be computed, once the displacements $\mathbf{u}_{i+1} = \mathbf{u}_i + \Delta \mathbf{u}_i$ are known. Expressing the equilibrium equation at this time step and using these difference relations results in a set of nonlinear algebraic equations in the nodal displacements \mathbf{u}_{i+1}

$$\mathbf{0} = \mathbf{R}(\mathbf{u}_{i+1}) = \mathbf{P}_{i+1} - \mathbf{F}_s(\mathbf{u}_{i+1}) - \mathbf{M}\ddot{\mathbf{u}}_{i+1}(\mathbf{u}_{i+1}) - \mathbf{C}\dot{\mathbf{u}}_{i+1}(\mathbf{u}_{i+1})$$

The application uses a Newton-Raphson iterative solution procedure to solve this nonlinear algebraic equation. This scheme results in a linearized model of the nonlinear equation at the current state for each iteration $j=1, 2, \dots$:

$$(\mathbf{a}_1 \mathbf{M} + \mathbf{a}_2 \mathbf{C} + \mathbf{a}_3 \mathbf{K}_{i+1}^j) \Delta \mathbf{u}^j = \mathbf{P}_{i+1} - \mathbf{F}_s(\mathbf{u}_{i+1}^j) - \mathbf{M}\ddot{\mathbf{u}}_{i+1}^j - \mathbf{C}\dot{\mathbf{u}}_{i+1}^j$$

where the constants a_1 , a_2 , and a_3 are constants and for a shear-building the Mass matrix, \mathbf{M} , and stiffness matrix, \mathbf{K} , are as defined below:

$$M = \frac{1}{g} \begin{bmatrix} w_1 & & \phi \\ & w_2 & \\ \phi & & w_n \end{bmatrix}$$

$$k = k_s + k_g$$

$$k_s = \begin{bmatrix} k_1+k_2 & -k_2 & & \phi \\ -k_2 & k_2+k_3 & -k_3 & \\ & -k_3 & \ddots & k_{n-1}+k_n & -k_n \\ \phi & & & -k_n & k_n \end{bmatrix}$$

$$k_g = \begin{bmatrix} -\frac{p_1}{h_1} & -\frac{p_2}{h_2} & +\frac{p_2}{h_2} & & \phi \\ +\frac{p_2}{h_2} & -\frac{p_2}{h_2} & -\frac{p_3}{h_3} & +\frac{p_3}{h_3} & \phi \\ & +\frac{p_3}{h_3} & \ddots & -\frac{p_{n-1}}{h_{n-1}} & \frac{p_n}{h_n} & +\frac{p_n}{h_n} \\ \phi & & & +\frac{p_n}{h_n} & -\frac{p_n}{h_n} \end{bmatrix}$$

where $p_i = \sum_{j=i}^N w_j$ and $h_i =$ story height.
and $k_g = \phi$ if no PDelta effects.

Damping for this tool is provided assuming a Modal Damping assumption. In modal damping the C Matrix is defined as shown below:

$$C = M \left(\sum_{n=1}^N \frac{2 \zeta_n \omega_n}{M_n} \phi_n \phi_n^T \right) M$$

where for n^{th} mode $\zeta_n =$ damping ratio,
 $\omega_n =$ natural frequency, $\phi_n =$ eigenvector,
and $M_n =$ generalized mass.

Earthquake Excitation:

The approach used in this tool to impose earthquake loading on a structure is to use a uniform excitation approach, which results in the following equation of motion:

$$M\ddot{u}(t) + C\dot{u}(t) + F_s(u(t)) = -M\ddot{u}_g(t)$$

It should be noted, that when using this approach the displacements being solved for, $u(t)$, are relative displacements and not the total displacements.

For a more comprehensive review of the material presented in this theory section see the book "Dynamics of Structures", by Anil K. Chopra, specifically sections 1.7, 5.4, 5.7, 9.2 and 11.4.

Wind Excitation:

The stationary wind model typically used in straight-line winds is expressed as the sum of the mean and the fluctuating wind components:

$$U(z,t) = \bar{U}(z) + u(z,t) \quad (1)$$

where, z = a location (a height for building structures) (ft); $\bar{U}(z)$ = mean wind speed at z over an averaging time (e.g., 10 minutes, 1 hour); $u(z,t)$ = fluctuating wind speed at z .

Invoking the quasi-steady theory assumption, wind loads can be written as:

$$F(z,t) = \frac{1}{2} \rho C_D A U^2(z,t) \quad (2)$$

where ρ = air density; C_D = drag coefficient; A = tributary area. Based on this relationship, the dynamic wind loads are approximated as:

$$\tilde{F}(z,t) \approx \rho C_D A \bar{U}(z) u(z,t) \quad (3)$$

Note that the square of the fluctuating wind component, $u^2(z,t)$, is generally neglected because $\bar{U}(z)u(z,t)$ is much larger than $u^2(z,t)$.

The mean wind speed at location z in the EvW tool is defined based on the exposure conditions defined in ASCE 7 standard, which the generic form is expressed as:

$$\bar{U}(z) = \bar{b} \left(\frac{z}{33} \right)^{\bar{\alpha}} \left(\frac{88}{60} \right) V \quad (4)$$

where \bar{b} , $\bar{\alpha}$ = constants defined in ASCE 7 for exposure condition B , C , or D ; V = basic wind speed (3-sec gust in ASCE 7) in mile per hour (mph).

The fluctuating wind (u) in stationary winds is modeled as a wind spectrum model in the frequency domain. For the EvW tool, the Kaimal wind spectrum model (Kaimal et al. 1972; also reported in Simiu and Scanlan, 1996) is employed:

$$S_u(z, f) = u_*^2 \cdot \frac{200z}{\bar{U}(z)} \cdot \frac{1}{\left[1 + 50 \cdot \frac{fz}{\bar{U}(z)} \right]^{5/3}} \quad (5)$$

where, $S_u(z, f)$ = power spectral density (PSD) of longitudinal fluctuating wind at location z ; f = frequency in Herz (Hz); u_* = friction velocity.

In addition, the Davenport coherence function between two arbitrary locations (represented by subscripts r and s) are utilized to describe correlated fluctuating winds (Davenport 1968).

$$Coh(f) = \exp \left[- \frac{C_z f |z_r - z_s|}{0.5 [\bar{U}(z_r) + \bar{U}(z_s)]} \right] \quad (6)$$

where C_z = exponential decay coefficient, generally taken as 10 from structural design viewpoint (e.g., Simiu and Scanlan, 1996).

Based on the PSD of fluctuating wind and the coherence function, the cross PSD (CPSD) of fluctuating wind is expressed in the following form, neglecting quadratic wind term,

$$S_{rs}(f) = \sqrt{S_{rr}(f) \cdot S_{ss}(f)} \text{Coh}(f) \quad (7)$$

Accordingly, the PSD matrix $G(z, \omega)$ of two-dimensional n -variate (n locations) wind fields is comprised:

$$G(f) = \begin{bmatrix} S_{11}(f) & S_{12}(f) & \cdots & S_{1n}(f) \\ S_{21}(f) & S_{22}(f) & \cdots & S_{2n}(f) \\ \vdots & \vdots & \cdots & \vdots \\ S_{n1}(f) & S_{n2}(f) & \cdots & S_{nn}(f) \end{bmatrix} \quad (8)$$

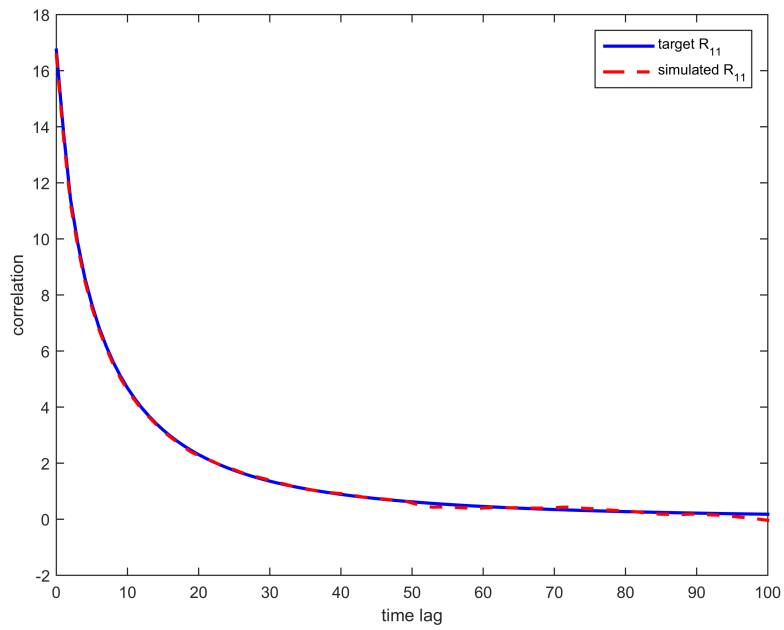
In the EvW tool, discrete frequency function with the fast Fourier Transform (FFT) proposed by Wittig and Sinha (1975) is adopted as the wind simulation scheme in view of its simplicity and fast computation. This scheme is based on the generation of the discrete frequency functions which correspond to the Fourier transform of the time series, and then using the FFT algorithm to obtain the actual time series. Discrete time series is simulated using the following model.

$$y_p(n\Delta t) = \frac{1}{N} \sum_{k=0}^N Y_p(k\Delta f) \exp\left(j \frac{2\pi kn}{N}\right) \quad (8)$$

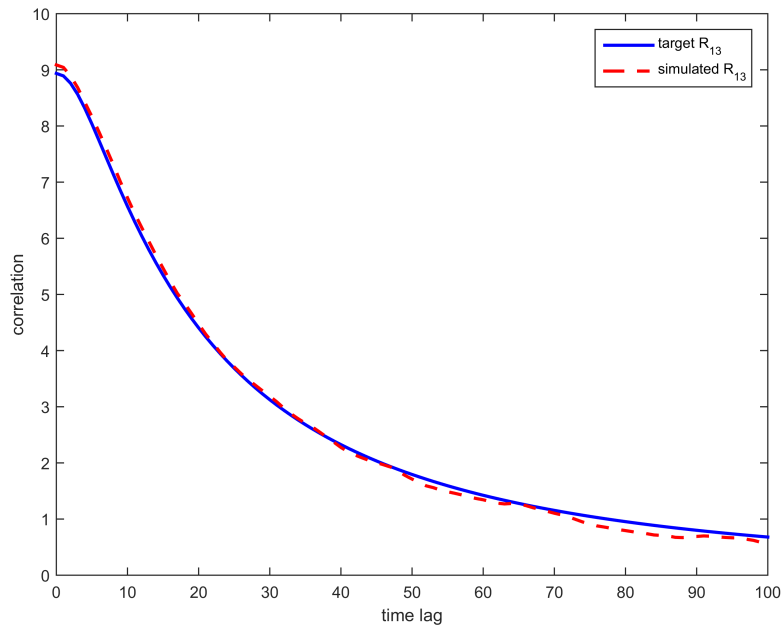
$$Y_p(k\Delta f) = \sum_{i=0}^p H_{pi}(k\Delta f) \varepsilon_{ik} \sqrt{2f_c N}$$

where, $H_{pi}(k\Delta f)$ = a lower triangular matrix by Cholesky decomposition of one-sided PSD matrix, $G(f)$; f_c = cut-off frequency (Hz), $\varepsilon_{ik} = \xi_{ik} + j\eta_{ik}$ = complex Gaussian random number with zero mean and variance of 0.5, $\Delta t = 1/2f_c$. Please note that this scheme has also been adopted as one of four wind simulation schemes in the NatHaz on-line wind simulator (NOWS), which is a web-enabled tool available at <http://windsim.ce.nd.edu> (Kwon and Kareem 2006).

A numerical example with three simulated heights such as 115 ft, 131 ft, and 459 ft is selected to demonstrate the validity of the wind simulation in the EvW tool. The mean wind speeds corresponding to the heights are assumed to be 100.7 mph, 102 mph and 114.3 mph, respectively. Figure 5 shows comparison of auto- (at the first height, R_{11}) and cross-correlation functions (between the first and the third heights, R_{13}) between theoretical (target) and simulated results where theoretical correlation functions are obtained through the Wiener-Khinchine transformation of theoretical PSD/CPSD of fluctuating wind (Eq. 7). It is observed that overall, the two results show very good agreements, which corroborate the efficacy of the wind simulation scheme.



(a)



(b)

Figure 5. Comparison between theoretical and simulated correlation functions: (a) auto-correlation functions at the first height; (b) cross-correlation functions between the first height and the third height 3.

References

- Kaimal, J. C., Wyngaard, J. C., Izumi, Y., and Cote, O. R. (1972). "Spectral characteristics of surface-layer turbulence." *Journal of Royal Meteorological Society*, 98, 563-589.
- Kwon, D., and Kareem, A. (2006). *NatHaz on-line wind simulator (NOWS): Simulation of Gaussian multivariate wind fields*, NatHaz Modeling Laboratory Report, University of Notre Dame, <http://windsim.ce.nd.edu>.
- Simiu, E., and Scanlan, R. H. (1996), *Wind effects on structures*, Third edition, John Wiley & Sons, Inc.
- Wittig, L. E., and Sinha, A. K. (1975). "Simulation of multicorrelated random processes using the FFT algorithm." *Journal of the Acoustical Society of America*, 58(3), 630-633.

12.2 Verification Examples:

A number of verification examples are provided to demonstrate the functionality and that the mathematics of the implementation match the theory. A test protocol also exists to test the functionality.

Example 1: Single-Story Linear Elastic Building

This is an example of a Single-story elastic building subjected to the ELCentro ground motion and a separate wind load. Its purpose is to study the response for a single degree-of-freedom structure subjected to earthquake and wind loads.

Building properties

Building properties are adopted from an example of ASCE-7-10.

Basic wind speed at reference height in exposure C = 90 mi/h

Type of exposure = B

Building height $h = 600$ ft

Building width $B = 100$ ft

Building depth $L = 100$ ft

Building natural frequency $n_1 = 0.2$ Hz

Damping ratio $\zeta = 0.01$

Mean along-wind force coefficient $C_{fx} = 1.3$

Mode exponent = 1.0

Building density = $12 \text{ lb/ft}^3 = 0.3727 \text{ slugs/ft}^3$

Air density = $0.0024 \text{ slugs/ft}^3$

Procedure

User starts EVW app and enters the following data, as shown in Figure 6.

Input Forces

Earthquake:

Input Motion: ELCentro

Scale Factor: 0.001

Wind:

Exposure Category: B

Gust Wind Speed: 90

seed: 100

Building Properties

Number Floors: 1
 Building Weight: 2.77795e7 k
 Shape: Square Height: 7200 in Width: 1200 in
 Drag Coefficient: 1.3
 Story Stiffness: 1.136978427005494e05 k/in
 Damping Ratio: 0.01
 Disable PDelta effects, i.e. uncheck the Include PDelta box.

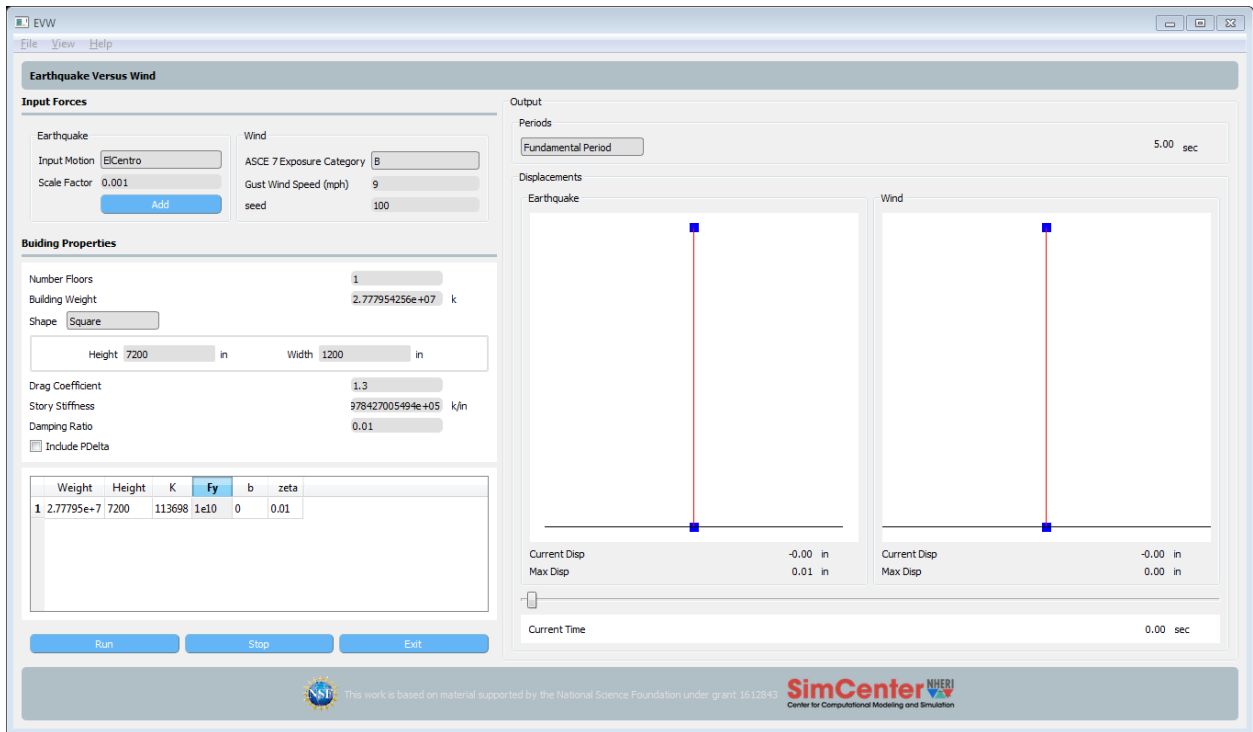


Figure 6: Program Display after Example 1 Inputs entered

Check out results:

Click 'Run' to see the animation on the right side of the window.

Click 'Stop' to stop the animation.

On the top of the window, under the 'View' tab (Fig. 7), there are several graphics to explore.

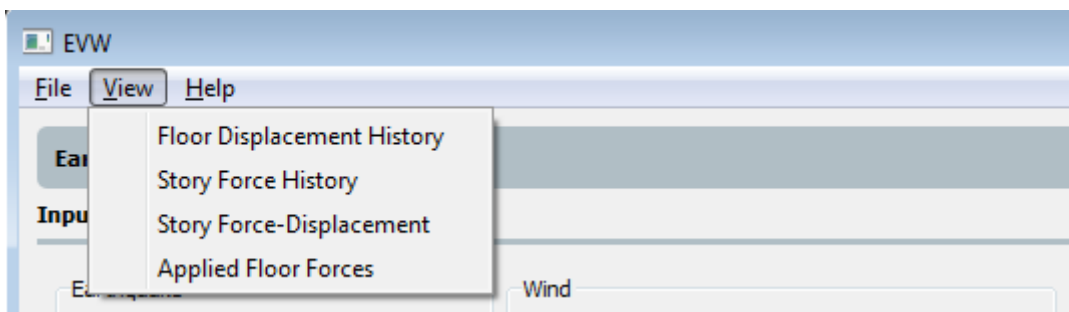


Fig. 7 View Menu Selection

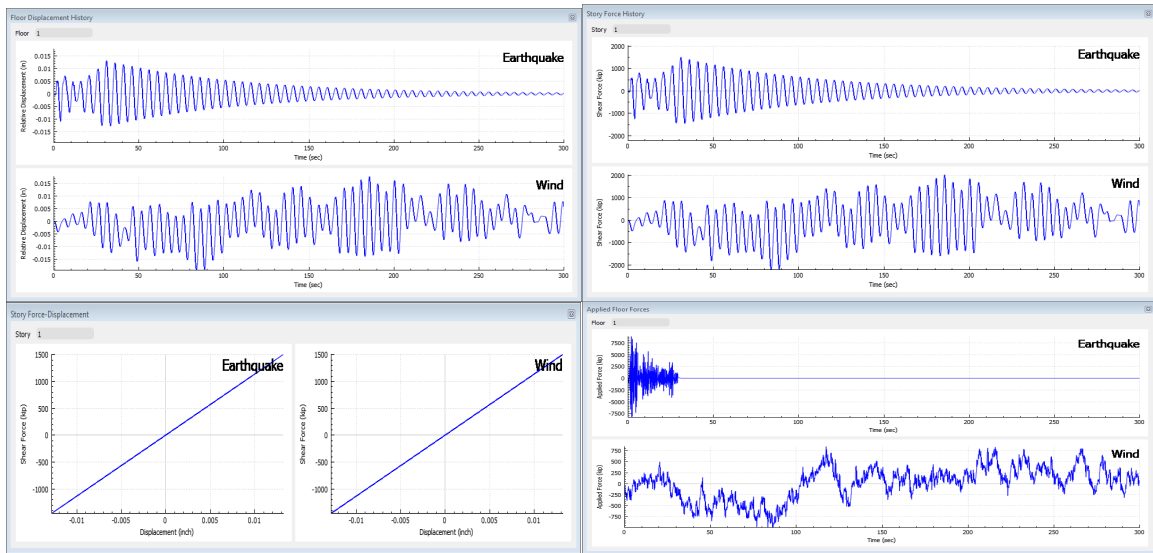


Figure 8: All Views for Example 1

Verifications

The EVW app is verified by the attached Matlab script EVW_SingleStory.m, where displacement at the top story of the structure is plotted in Figure 9, which can be compared with EVW output presented in Figure 8.

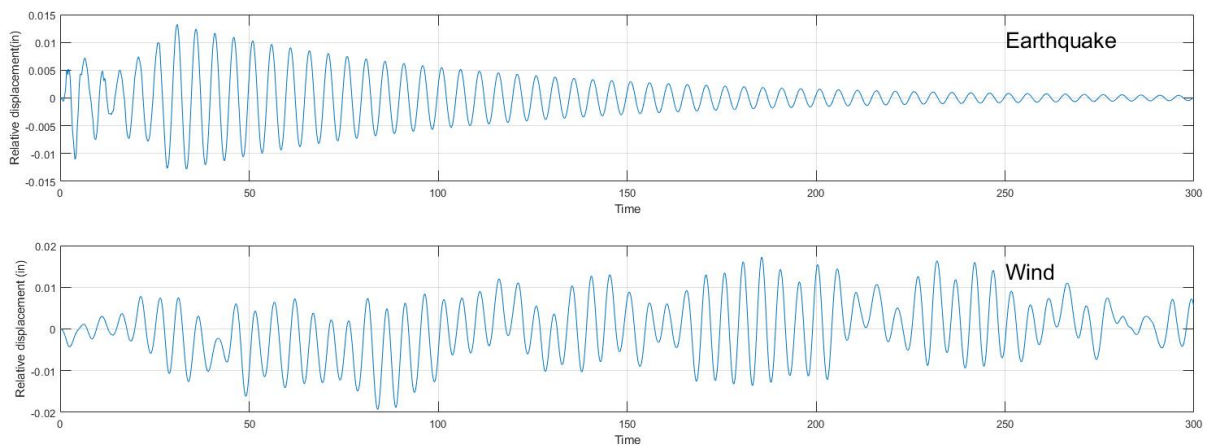


Figure 9: Matlab Comparison

Example 2: Single-Story Elastic Nonlinear Building

This is an example of a Single-story elastic building subjected to ELCentro ground motion and wind load. Its purpose is to study the effects of nonlinearity on the response for a single degree-of-freedom structure subjected to earthquake and wind loads.

Building properties

Building properties are adopted from an example of ASCE-7-10.

Basic wind speed at reference height in exposure C = 90 mi/h

Type of exposure = B

Building height $h = 600$ ft

Building width $B = 100$ ft

Building depth $L = 100$ ft

Building natural frequency $n_1 = 0.2$ Hz

Damping ratio $\zeta = 0.01$

Mean along-wind force coefficient $C_{fx} = 1.3$

Mode exponent = 1.0

Building density = $12 \text{ lb/ft}^3 = 0.3727 \text{ slugs/ft}^3$

Air density = $0.0024 \text{ slugs/ft}^3$

Procedure

User starts EVW app and enters the following (Fig. 1):

Input Forces

Earthquake:

Input Motion: ELCentro

Scale Factor: 0.001

Wind:

Exposure Category: B

Gust Wind Speed: 90

seed: 100

Building Properties

Number Floors: 1

Building Weight: 2.77795×10^7 k

Shape: Square Height: 7200 in Width: 1200 in

Drag Coefficient: 1.3

Story Stiffness: $1.136978427005494 \times 10^5$ k/in

Damping Ratio: 0.01

Disable PDelta effects, i.e. uncheck the Include PDelta box.

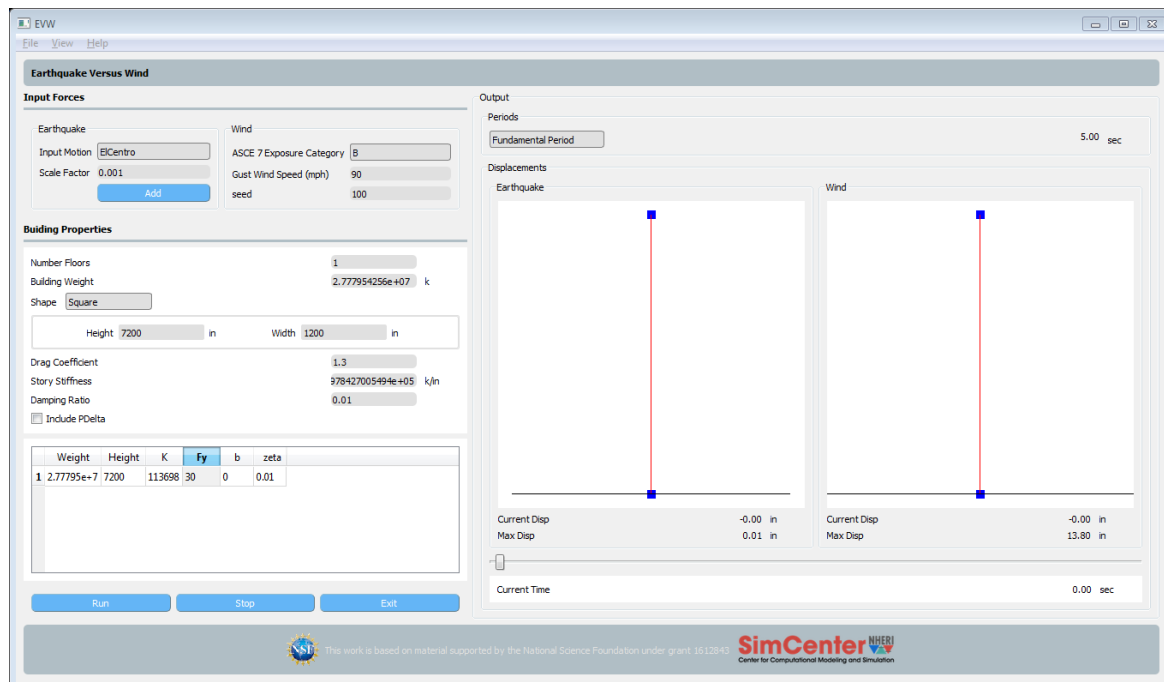


Figure 10: Program Display after Example 2 Inputs

Check out result:

Click 'Run' to see the animation on the right side of the window.

Click 'Stop' to stop the animation.

On the top of the window, under the 'View' tab, there are several graphics to explore.

Change 'Fy' value to see the changes in results.

Verification:

The EVW app is verified by the attached Matlab script EVW_SingleStory.m.

Displacements calculated by EVW are shown in Figure 11

Displacements calculated by EVW_SingleStory.m are shown in Figure 12.

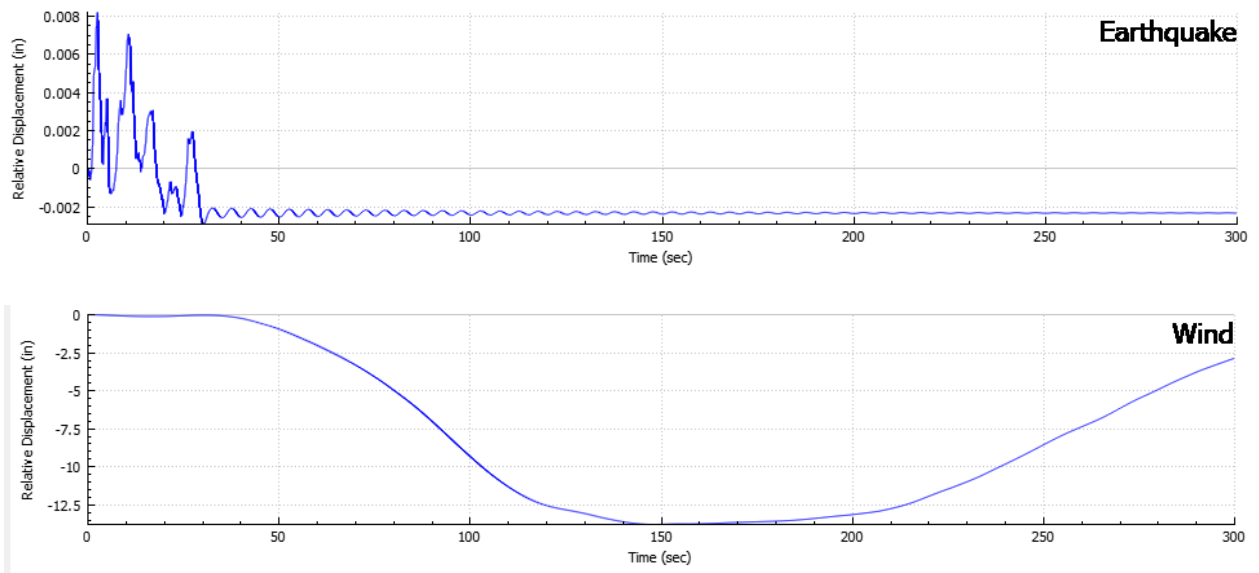


Figure 11

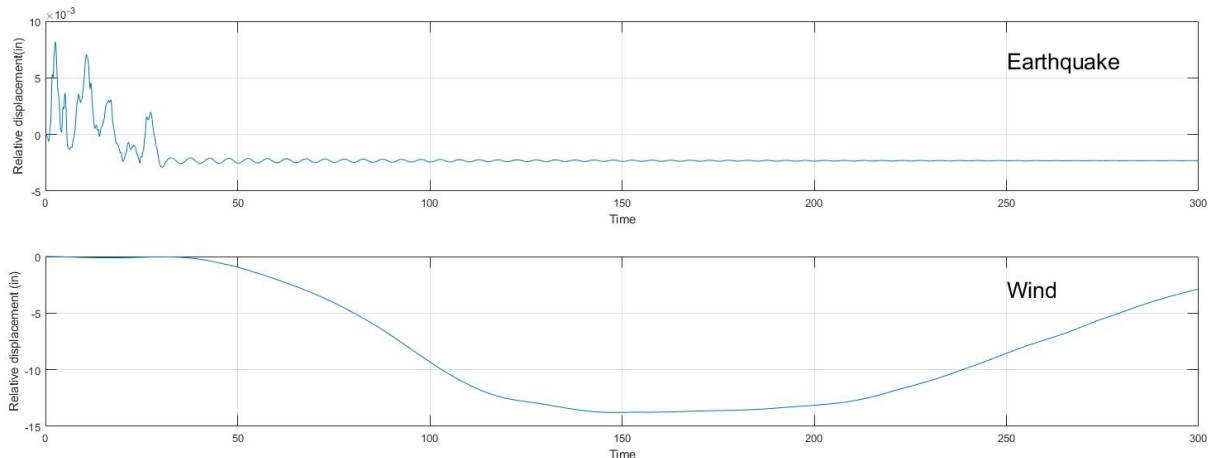


Figure 12: Matlab Comparison

Example 3: Multi-Story Elastic Building

This is an example of a multi-story elastic building subjected to ELCentro ground motion and wind load. Its purpose is to study the response for a multiple degree-of-freedom structure subjected to earthquake and wind loads.

Building properties

Building properties are adopted from an example of ASCE-7-10.

Basic wind speed at reference height in exposure C = 90 mi/h

Type of exposure = B

Building height $h = 600$ ft

Building width $B = 100$ ft

Building depth $L = 100$ ft

Building natural frequency $n_1 = 0.2$ Hz

Damping ratio $\zeta = 0.01$

Mean along-wind force coefficient $C_{fx} = 1.3$

Mode exponent = 1.0

Building density = $12 \text{ lb/ft}^3 = 0.3727 \text{ slugs/ft}^3$

Air density = $0.0024 \text{ slugs/ft}^3$

Procedure

User starts EVW app and enters the following (Fig. 1):

Input Forces

Earthquake:	Input Motion: ELCentro	Scale Factor: 0.001
Wind:	Exposure Category: B	Gust Wind Speed: 90
seed: 100		

Building Properties

Number Floors: 60
Building Weight: 2.77795×10^7 k
Shape: Square Height: 7200 in Width: 1200 in
Drag Coefficient: 1.3
Story Stiffness: 2.81123×10^6 k/in
Damping Ratio: 0.01
Disable PDelta effects, i.e. uncheck the Include PDelta box.

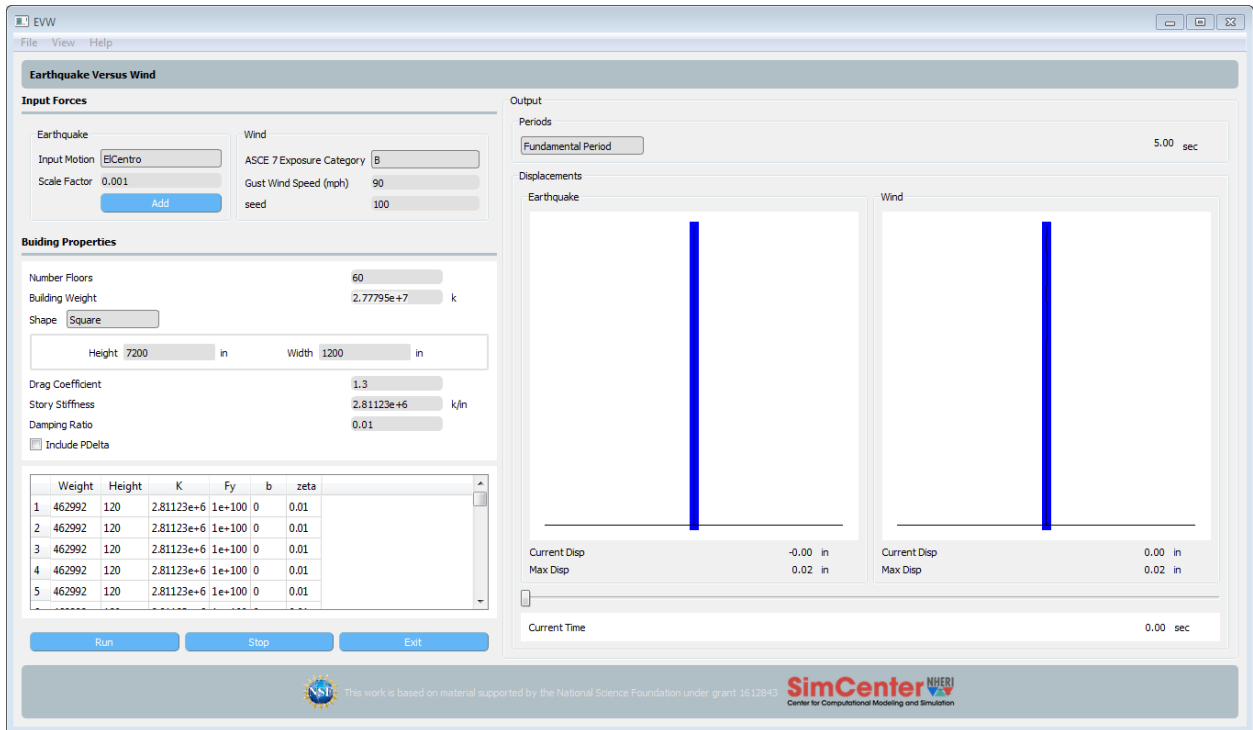


Figure 13: Program Display after Example 3 Inputs.-

Check out results

Click 'Run' to see the animation on the right side of the window.

Click 'Stop' to stop the animation.

On the top of the window, under the 'View' tab, there are several graphics to explore.

Verifications

The EVW app is verified by the attached Matlab script EVW_MultiStory_Linear.m.

Displacements calculated by EVW are shown in Fig. 14.

Displacements calculated by EVW_MultiStory_Linear.m are shown in Fig. 15.

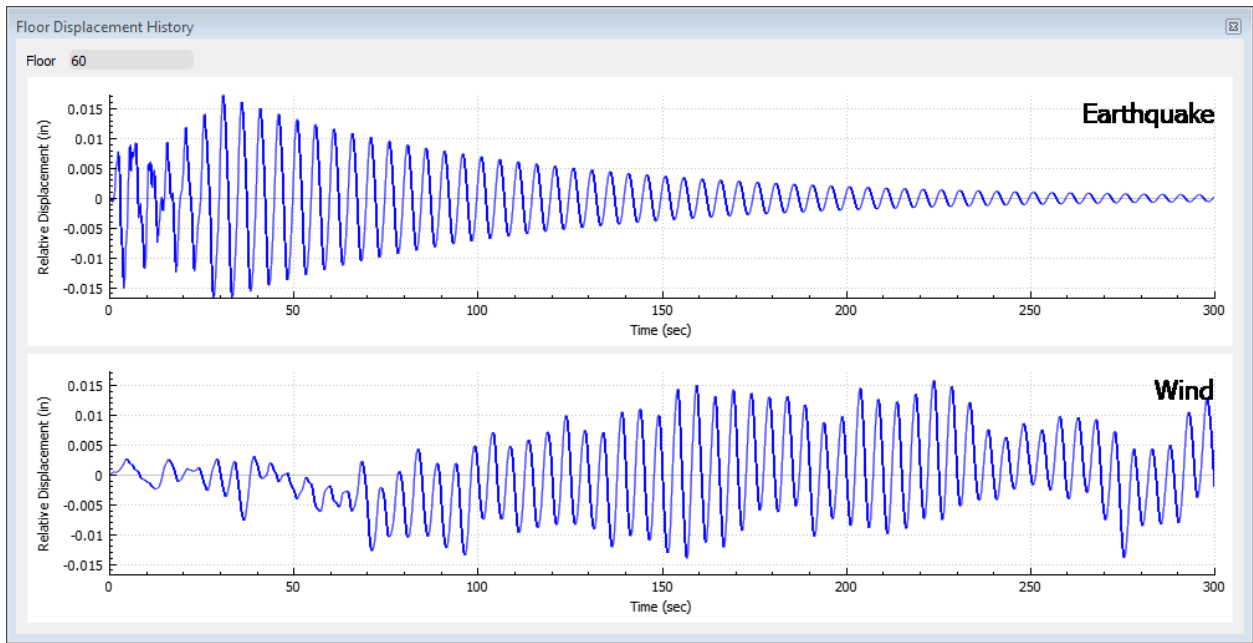


Figure 14: Application Output

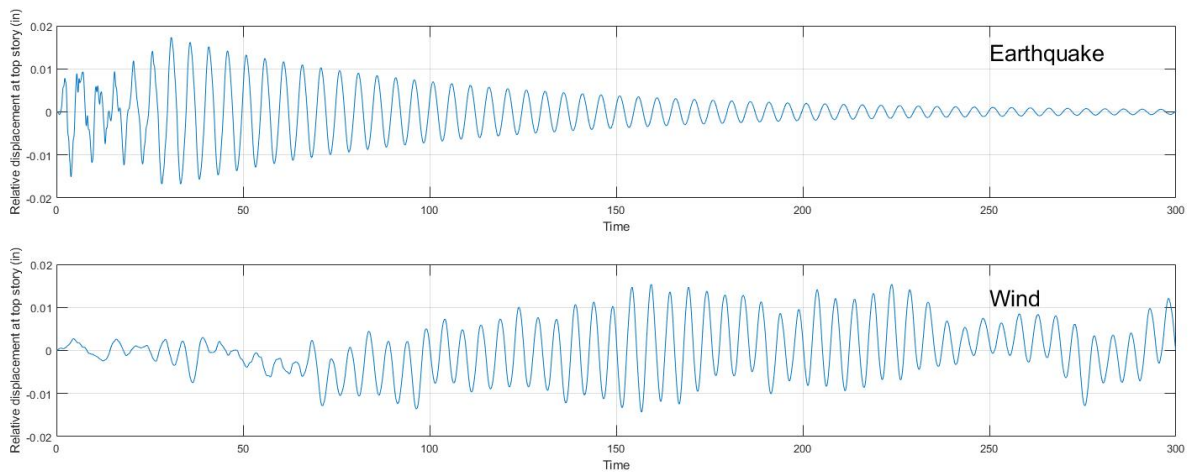


Figure 14: Matlab Output

Example 4: Multi-Story Elastic Non-Linear Building

This is an example of a multi-story elastic building subjected to ELCentro ground motion and wind load. Its purpose is to study the effect of nonlinearity on the response for a multiple degree-of-freedom structure subjected to earthquake and wind loads.

Building properties

Building properties are adopted from an example of ASCE-7-10.

Basic wind speed at reference height in exposure C = 90 mi/h

Type of exposure = B

Building height $h = 600$ ft

Building width $B = 100$ ft
 Building depth $L = 100$ ft
 Building natural frequency $n_1 = 0.2$ Hz
 Damping ratio $\zeta = 0.01$
 Mean along-wind force coefficient $C_{fx} = 1.3$
 Mode exponent = 1.0
 Building density = $12 \text{ lb/ft}^3 = 0.3727 \text{ slugs/ft}^3$
 Air density = $0.0024 \text{ slugs/ft}^3$

Procedure

User starts EVW app and enters the following (Fig. 1):

Input Forces

Earthquake: Input Motion: ELCentro Scale Factor: 0.001
 Wind: Exposure Category: B Gust Wind Speed: 90
 seed: 100

Building Properties

Number Floors: 5
 Building Weight: 2.77795×10^7 k
 Shape: Square Height: 7200 in Width: 1200 in
 Drag Coefficient: 1.3
 Story Stiffness: 2.81123×10^6 k/in
 Damping Ratio: 0.01
 Disable PDelta effects, i.e. uncheck the Include PDelta box.
 Fy: 30

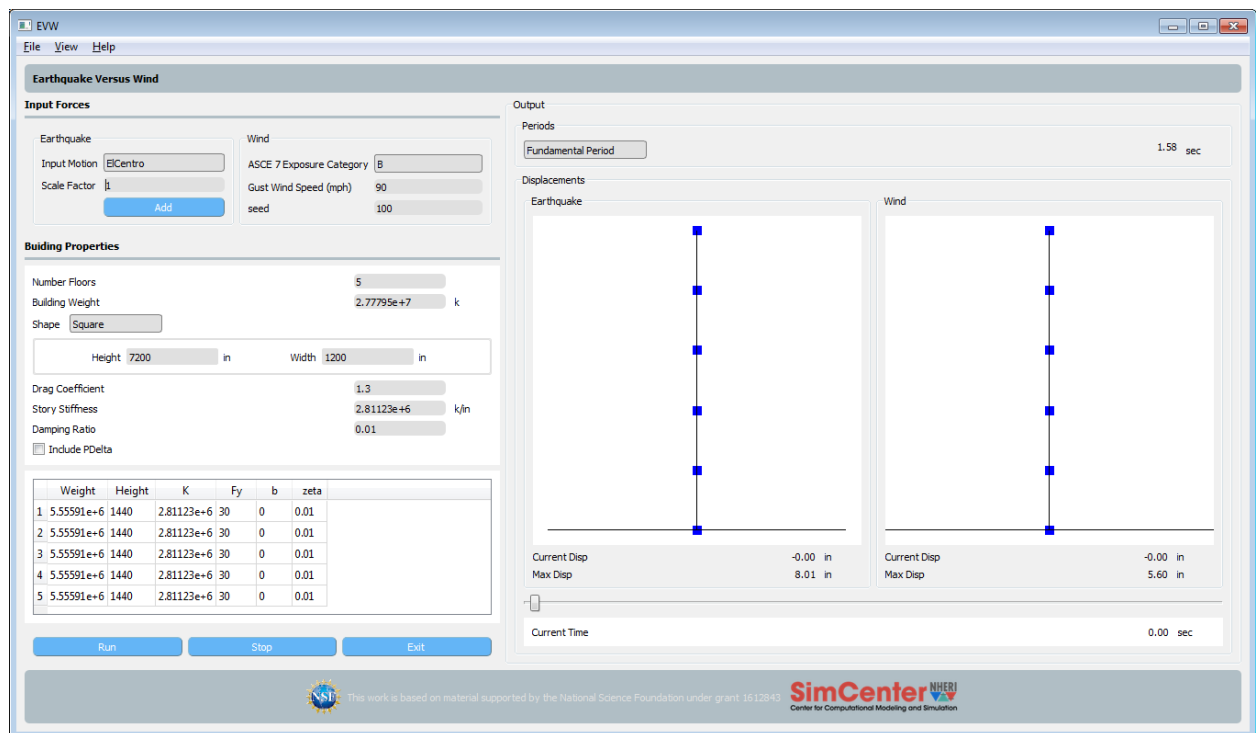


Figure 15: Application State after Example 4 Inputs

Check out results

Click 'Run' to see the animation on the right side of the window.

Click 'Stop' to stop the animation.

On the top of the window, under the 'View' tab, there are several graphics to explore.

Verifications

The EVW app is verified by the attached Matlab script EVW_MultiStory_NonLinear.m.

Displacements calculated by EVW are shown in Figure 16.

Displacements calculated by EVW_MultiStory_NonLinear.m are shown in Figure 17.

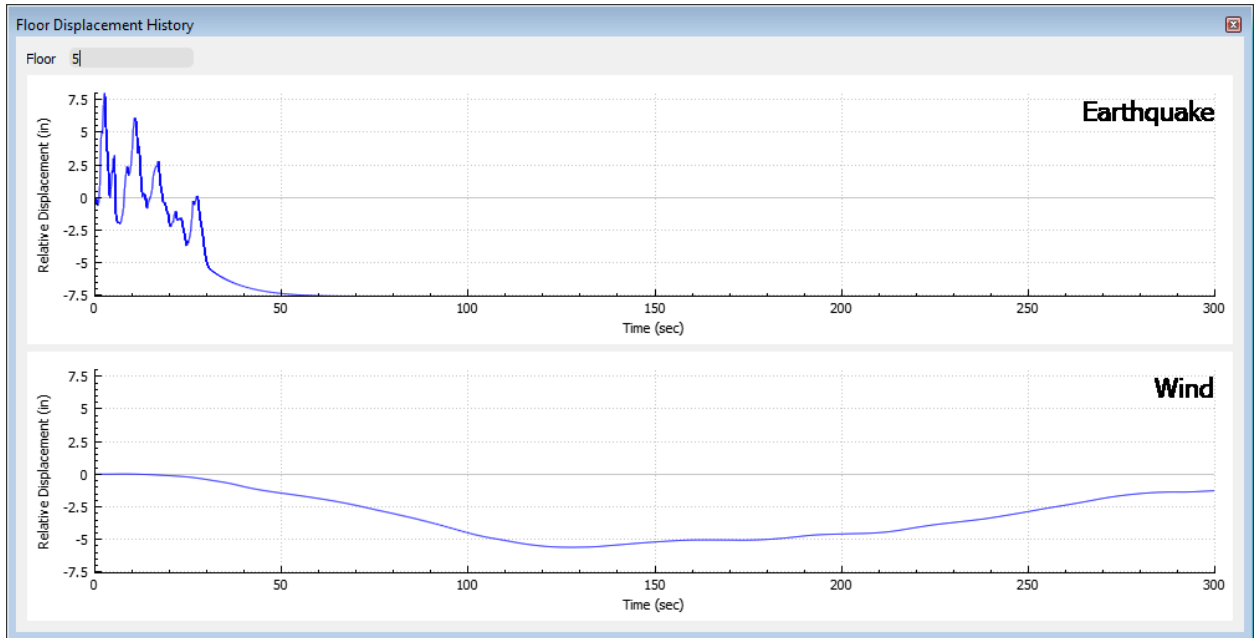


Figure 16: Application Output

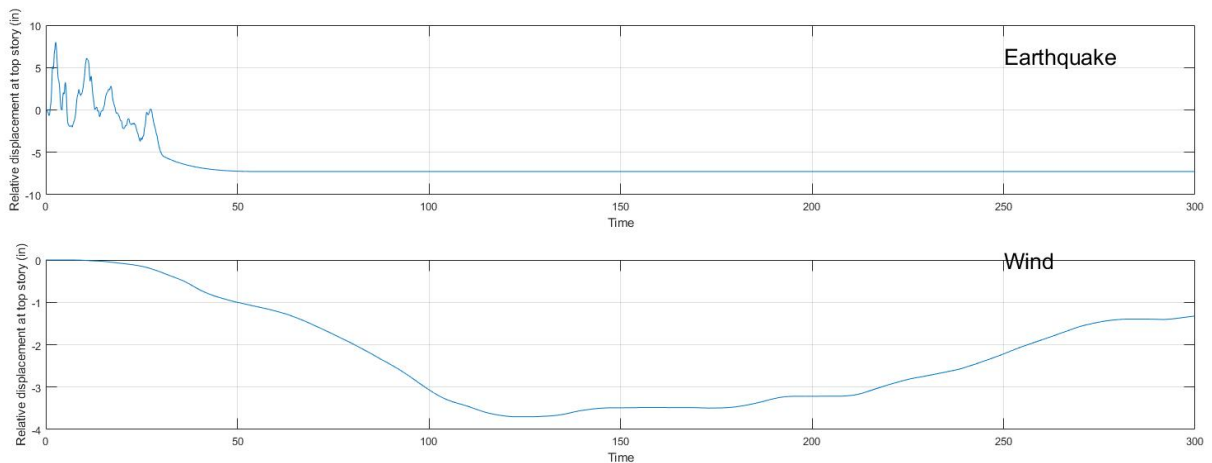


Figure 17: Matlab Output

Example 5: User able to add their own ground motion to the tool. The input format for a new motion is a JSON file containing an object with the records name, delta t, and the recorded points in an array “data”. The units for the data points are g.

A test of user requirement 5.a.

```
{
  "numPoints": 1560,
  "name": "eLC",
  "dT": 0.02000,
  "accel_data": [
    0.00000,
    0.00630,
    ..
    ..
  ]
}
```

An example file, eLC.json, is provided in the tool example directory on github. This motion is the same as the ELCentro motion, so results can be verified by using any of the above examples; it is the ability of user to add a motion that is being tested.

Testing Procedure:

- User downloads example JSON file containing record.
- User starts tool
- User selects add button in Input Motion frame and loads the file.
- User should be presented with results for new motion.
- User can compare with other motions, by clicking on Input motion pull down and selecting a different motion.

Example 6: User able to save and load any saved set of options. Test of user requirement 3.

Testing Procedure:

- User starts tool
- User makes any number of changes.
- User selects save from file menu and provides name.
- User exits tool and starts again.
- User selected open from file menu, navigates and selects the file they just saved. Properties and results should be as last saved.

13. Implementation on DesignSafe-ci.

The tool is built as a stand-alone desktop application for use on machines running the Windows and macOS operating systems. It currently does not utilize DesignSafe-ci

resources. It is made for download through a webpage devoted to the tool on a page hosted by DesignSafe-ci:

<https://simcenter.designsafe-ci.org/learning-tools/evw-application/>

14. User Training/ Support:

User Training consists of an online video available from the tool webpage that demonstrates tool use. The tool will be presented in user workshops scheduled to start in year 3 and at NHERI Summer Institute.

User support at present is a slack channel dedicated to the tool. SimCenter member McKenna will monitor this channel.

3. Requirements:

A **user group** consisting of Professors teaching courses in dynamics, wind and earthquake engineering and graduate students who have previously taken such courses was convened. This group consists of the following:

- SimCenter members: Prof. Ahsan Kareem, Prof. Laura Lowes, Frank McKenna, Chaofeng Wang, Wael Elhaddad,
- Non-SimCenter: Prof. Michael Scott (Oregon State University), Prof Dae Kun Kwon (Notre Dame)

Dr McKenna conversed individually and in group settings with members of this group. The following are the main user requirements identified by the group:

#	Description	Priority	Version
1	Ability to have side by side comparison of earthquake and wind responses	M	1.0
2.a	User able to subject building to different earthquake motions: a) User able to select from a range of ground motions stored as files on user system.	M	1.0
2.b	b) User able to scale motion magnitude.	M	1.0
3.q	User able to subject building to different wind simulations: a) User to select different exposure categories	M	1.0
3.b	b) User able to vary wind speed	M	1.0
4.a	User able to modify properties of building and see effect on response: a) Number of Floors	M	1.0
4.b	b) Building Height and Weight	M	1.0
4.c	c) Stiffness and Yield properties of Stories	M	1.0
4.d	d) Floor Weights	M	1.0
4.e	e) Modal Damping Ratios	D	1.0
4.f	f) Building Shape & Dimensions	M	1.0
4.g	g) Drag Coefficient	M	1.0
5	User able to turn on/off the inclusion of PDelta effects	D	1.0

6	User able to save current building properties into a file and subsequently load at any later instance in time.	D	1.0
7.a	User able to view how input forces and response parameters change with time: a) Plot of forces applied at floor level versus time.	M	1.0
7.b	b) Plot of Floor displacements and story shear forces versus time.	M	1.0
7.c	c) Plot of Shear Forces versus Interstory Disp	M	1.0
7.d	d) Plot of Shear Forces versus Time	M	1.0
8	Visibly highlight current location in history plots (disp, story force, acceleration)	D	
9	Ability to plot response of multiple buildings	P	
10	Ability to compare current results with previous result	D	

M=Mandatory, D=Desirable, O=Optional, P=Possible Future

9. Staffing with Required Expertize:

Tool development requires user interface design, user interface programming, finite element programming for earthquake simulation and computational fluid dynamics for wind/water-structure coupling if necessary.

- UI Programming/FE Programming: Frank McKenna
- CFD Programming: Prof Dae Kun Kwon, Wael Elhaddad
- Tool Testing: Prof. Ahsan Kareem, John Lowe, Chaofeng Wang, Wael Elhaddad, KD, Laura Lowes
- V&V: Frank McKenna, Ahsan Kareem, Chaofeng Wang

6. Schedule:

Version	Release	Requirements
1.0	June 2018	1,2,3,4,5,6,7
2.0	T.B.D	8,9,10
3.0		

7. Milestones:

- April 2018, Prototype V0.1 released to leadership and code placed into Github.
- June 2018. Initial release of V1.0 to public though DesignSafe-ci website.

8. Communications among team members while tool under development:

1. Weekly meeting between Designer and Programmer while tool under active development.
2. Weekly show and tell with other SimCenter programmers to elicit feedback while tool under active development.

3. Meeting between Programmer and those testing tool to go over bugs encountered during testing and develop testing protocol.
4. Before release of tool, provide tool to user group members for testing and additional feedback.

11. Documentation:

Documentation for this tool will consist of the following:

- 1) This document
- 2) Short video documenting tool use.
- 3) Verification examples input files and corresponding Matlab .m files.

This document and the short video are available at the tool webpage.

(<https://simcenter.designsafe-ci.org/learning-tools/evw-application/>). The examples are available from the tools Github page. (<https://github.com/NHERI-SimCenter/EVW>)