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Database-Assisted Design: Performance-Based Approach for Dynamically Sensitive Steel and Reinforced Concrete Structures

Daniel M. Rhee
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Brian Carman
Charys Clay

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Abstract

This Technical Note presents the User's Manual for the DAD_PBD version 2.0 software that is a user-friendly tool for the advanced structural design of dynamically sensitive steel and reinforced concrete buildings. The software utilizes the Database-Assisted Design (DAD) procedure, which was developed and continuously improved at NIST. The method employs time-domain analysis, directional aerodynamic pressure data, and wind climatological data specific to a local site to design a structure in the site for wind, demonstrating superior performance in the estimation of the peak responses (e.g., Demand-to-Capacity Index, inter-story drift ratio, acceleration, Deformation Damage Index) from combined wind effects and the consideration of wind directionality effects.

The DAD method has been advanced over the past decade, improving its accuracy and practicality. The most recent work at NIST includes Python-based DAD_PBD software incorporating commercially available software, ETABS, to enhance accessibility for practicing structural engineers and improve computational efficiency. The previous version of the software was only applicable to rectangular-shaped steel-framed buildings.

To address these limitations, the DAD_PBD software was further enhanced with the following features: 1) expansion of its application to reinforced concrete buildings consisting of shear walls, columns, and link beams through the use of commercial design software for calculating the biaxial bending and axial force interaction diagrams for reinforced concrete members, 2) assignment of distributed wind loads to building envelope, which is a more appropriate approach for irregular-shaped buildings and buildings with asymmetric structural systems, 3) parallel run of ETABS analyses, which significantly reduces the computational time required for constructing response surfaces for design parameters. Any features previously introduced in the DAD_PBD version 1.0 software for steel-framed buildings remain relevant to this version. The DAD_PBD version 2.0 software enables structural engineering practitioners to execute advanced structural design of irregular-shaped buildings with steel and reinforced concrete members under the concept of performance-based wind design.

This report also showcases a design example of 45-story reinforced concrete buildings, illustrating the software's practical application.

Keywords

Climatological data; Database-Assisted Design (DAD); ETABS; High-rise buildings; Irregular-shaped buildings; Parallel computing; Reinforced-Concrete Structures; Steel structures; Structural design; Structural dynamics; Wind effects.

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Acknowledgments

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Author Contributions

Daniel M. Rhee: Methodology, Software, Visualization, Investigation, Validation, Writing- Original draft preparation; **DongHun Yeo**: Conceptualization, Methodology, Project administration, Supervision, Writing- Reviewing and Editing; **Mehedy Mashnad**: Methodology, Project administration; **Brian Carman**: Methodology, Investigation, Validation, Writing- Original draft preparation; **Charys Clay**: Project administration.

1. Introduction

In recent decades, urban landscapes have seen a steady increase in the number of high-rise buildings and skyscrapers around the globe, which has led to great advances in the design of tall buildings for wind [1]. While the American Society of Civil Engineers (ASCE) 7 standard offers simplified analytical methods, they are not applicable to (i) dynamically sensitive buildings subjected to across-wind loading, vortex shedding, or aeroelastic phenomena or (ii) buildings with unusual shapes or response characteristics [2]. As a result, the wind tunnel procedure has become the common practice among structural engineers for buildings that are aerodynamically sensitive to the building shape [3-5]. Furthermore, there has been a paradigm shift for dynamically sensitive building design from prescriptive code-based design to a design based on specific performance objectives that may exceed those covered by codes and standards. These objectives can range from occupant comfort levels (e.g., acceleration limit) through serviceability levels (e.g., building drift limit) to strength and safety levels (e.g., continuous occupancy). A Prestandard for Performance-Based Wind Design (PBWD) that provides guidelines for PBWD was recently published by ASCE/SEI [6]. Because PBWD necessitates a detailed evaluation of building response to wind, the Prestandard requires that designers employ a linear or nonlinear response history analysis for advanced levels of building analysis and design. The Prestandard also acknowledges the inadequacy of the wind hazard curve based on the peak non-directional wind speed and the necessity of the hazard curve based on the expected responses of the building up to the MRI of interest.

The National Institute of Standards and Technology (NIST) has developed and continues to enhance the Database-Assisted Design (DAD) procedure for the advanced design of structures subjected to direction-dependent wind loads in local climates [7-9]. The DAD procedure accurately estimates the peak wind effects by coupling the response surfaces from time-domain analysis using time series pressure coefficients obtained from wind tunnel experiments or Computational Fluid Dynamics (CFD) simulations, along with site-specific directional extreme wind speed datasets obtained from measurements or simulations.

In recent years, the DAD_ETABS program was developed on the MATLAB platform [10] to incorporate the ETABS structural analysis software with the DAD procedure for advanced design of high-rise buildings [11]. However, a collaboration between NIST and Walter P Moore (WPM) structural engineers found that the MATLAB-based program might hinder adoption as a practical design tool due to the high cost of MATLAB licensing, which is not commonly used in structural engineering firms. Further suggestions for enhancing the practicality of the DAD procedure/software are reported in NIST Technical Note 2236 [12].

As a result, NIST and collaborators from practicing engineering firms WPM and Arup Group Limited (ARUP) have developed DAD_PBD using the open-source Python language [13], which is widely used by designers and software engineers in structural engineering firms. In addition, the DAD_PBD program includes a design parameter known as Deformation Damage Index (DDI). This index is crucial for assessing drift demands and potential damage in cladding and partition systems, thereby facilitating a sophisticated design for building envelope performance, as highlighted by the Prestandard [6]. The DAD_PBD has taken the first step in advancing the DAD procedure towards practical engineering design of high-rise buildings, in accordance with the PBWD concept [14].

This report presents an updated version of the DAD_PBD software, originally introduced in Technical Note 2293 [11]. The key improvements include 1) expanding its application to reinforced-concrete buildings, 2) introducing a method to assign transient wind loads on irregular-shaped buildings, and 3) significantly reducing calculation time by enabling parallel execution of ETABS analyses and data extraction on multiple computers.

This report provides an overview of the improved DAD_PBD procedure and software, along with the results of structural designs of a reinforced concrete shear wall building using the DAD_PBD. For a design example of a steel-framed building, refer to Technical Note 2293 [11].

2. User's Manual

2.1. Overview

The DAD_PBD software is only compatible with the Windows operating system and is applicable to dynamically sensitive buildings with steel-frame or Reinforced Concrete (RC) members. The current version supports buildings with rectangular plans and limited irregular shapes, characterized by four walls that vary linearly in height.

To carry out the DAD_PBD procedure, the program requires transient aerodynamic pressure data for the building of interest and site-specific climatological data. The aerodynamic pressure (C_p) data can be acquired through wind tunnel tests or Computational Fluid Dynamics (CFD) simulations, while the climatological data can be sourced from weather stations or simulations. Further details on these data sources are provided in Sections 2.5 and 2.7, respectively.

The DAD_PBD software enhances user-friendliness by controlling the ETABS software through the ETABS Application Programming Interface (API).

The overall procedure and flowchart of DAD_PBD are illustrated in Fig. 1. In the process diagram, the main algorithm of the DAD_PBD, written in Python, is within the dotted orange box, while the processes carried out in ETABS are in the blue solid box. The data acquired outside of the DAD_PBD software include the input data provided by the wind engineer (yellow dashed box) and the structural engineer (blue dashed box). The steps to execute the building design using the DAD_PBD software are as follows:

1. Determine Acceptance Criteria: Based on performance objectives, the user establishes the acceptance criteria for the design parameters of interest for the structural design (See Section 3.1 for example performance objectives and acceptance criteria for a design building).
2. Perform Preliminary Design: By applying the ASCE 7 gravity and wind loads [2], the user establishes the structural system and initial member sizes for the building and develops an ETABS model of the structure (Section 2.3).
3. Compute Time-History Wind Loads: Using the C_p data from the wind tunnel tests or CFD simulations, the software computes the time-history wind loads for each floor (Section 2.5). Note that this process occurs once and does not need to be repeated for iterative design.
4. Dynamic Analysis in ETABS: The software commands ETABS to apply the time-history wind loads for each floor and carry out dynamic analyses for various wind speeds and directions, generating time-histories of the structural response (e.g., internal forces on members, joint displacements, and joint accelerations). Note that nodes are referred to as joints in ETABS.

5. Construct Response Surfaces: The software constructs response surfaces as a function of wind speed and direction for different design parameters (e.g., Demand-to-Capacity Index (DCI[1]), inter-story drift ratio, floor acceleration, and DDI) (Section 2.6).
    - For RC buildings, the user inputs the rebar schedules and the biaxial bending and axial force interaction (i.e., PMM interaction) of the RC members.
6. Generate Design Response Curve: The acceptance criteria and their corresponding MRIs determined from Step 1 are entered into DAD_PBD software. The climatological data (i.e., site-specific directional extreme wind speed data) is projected onto the response surfaces, and design response curves based on MRI are generated (Section 2.7).
7. Check Design Responses: The software checks design responses at the MRI specified by the user against the corresponding acceptance criteria. If the responses exceed the acceptance criteria requirements, the member sizes (or rebar sizes in the case of RC building) should be redesigned, and Steps 4 to 6 should be repeated until all the acceptance criteria are met. Note that certain acceptance criteria may need to be iterated after the dynamic modal analysis. For instance, the maximum acceptable peak acceleration depends on the natural frequency of the structure and may need to be re-determined.

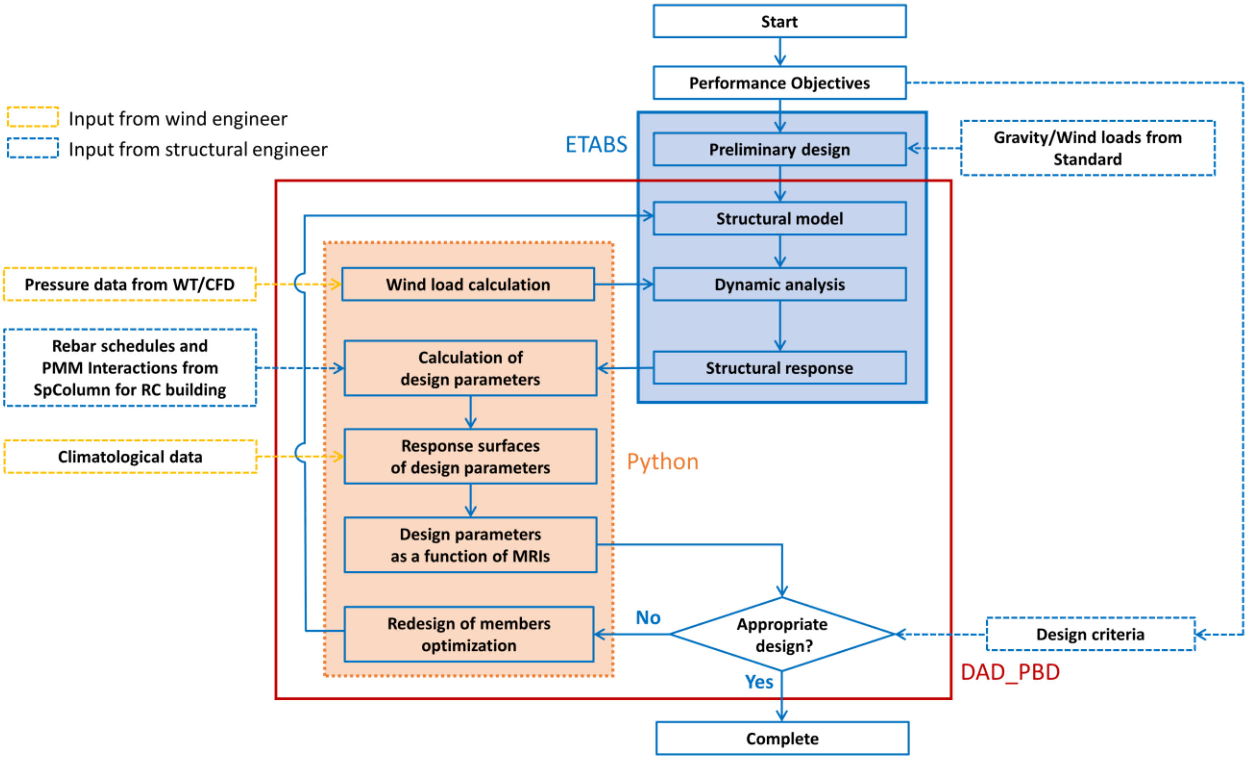

Fig. 1. Process diagram for DAD_PBD.

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[1] Note that DCI is different from the conventional Demand-to-Capacity (DCR). Refer to Section 2.6.1 for more details on DCI.

2.2. Required Software and Packages

The DAD_PBD software requires CSI ETABS for structural and dynamic analysis [15]. The software was developed using ETABS version 20, but any version 18 or later is compatible with the current DAD_PBD. It is critical to ensure that the "ETABSv1.dll" library file, which contains the ETABS API functions, is included in the ETABS program file folder. Refer to Section 2.4.1 for the detailed directory path for the dll file.

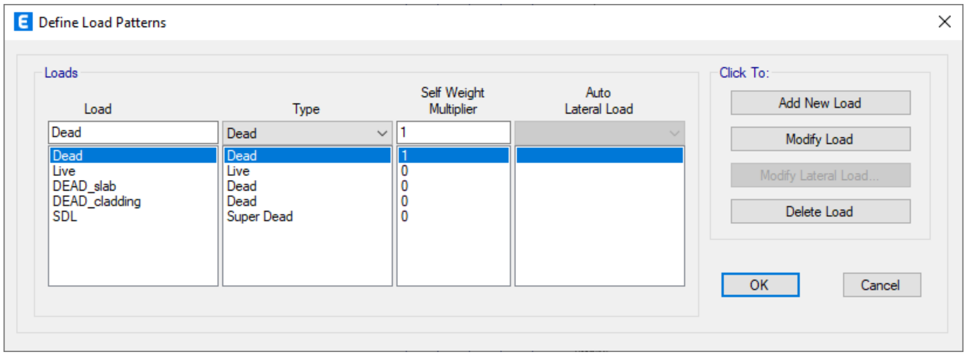
The DAD_PBD also requires the installation of the Python programming language along with the following packages and libraries: NumPy [16], h5py [17], SciPy [18], Matplotlib [19], Pythonnet [20], openpyxl [21], and pandas [22]. Though DAD_PBD was developed using Python version 3.8.11, it should remain compatible with any later version.

For calculating the PMM interaction diagrams of RC members, concrete design software is necessary for RC buildings in DAD_PBD. While SpColumn [23] was used in the development of DAD_PBD, any PMM program can be employed as long as its PMM input file format is consistent. Details of the format are specified in Appendix D.

2.3. Preliminary Design

Prior to starting the DAD procedure, an ETABS model of the preliminary design must be built, as discussed in Step 2 of Section 2.1. The DAD_PBD software supports the Main Wind Force Resisting System (MWFRS) for both steel-framed buildings, which include beams, columns, and braces, and RC buildings, which consist of columns, shear walls, and link beams. Refer to Section 3 of Technical Note 2293 [11] for a steel-framed building example and Section 3 of this report for an RC building example. The preliminary ETABS model is developed using the initial geometry of the structural members along with the gravity and wind loads defined by the ASCE 7 standards [2].

In the ETABS model, it is essential for the user to correctly define all types of gravity loads (e.g., dead load, live load, superimposed dead load) used in the preliminary design and ensure that all loads are included in the load patterns. Figure 2 shows an example of all gravity load patterns of the design example ETABS model. The load patterns can be displayed by navigating the "**Define Load Patterns**" in ETABS.



Load	Type	Self Weight Multiplier	Auto Lateral Load
Dead	Dead	1	
Dead	Dead	1	
Live	Live	0	
DEAD_slab	Dead	0	
DEAD_cladding	Dead	0	
SDL	Super Dead	0	

Fig. 2. Example definitions of load patterns of the preliminary design of a building.

Note that the names assigned to the load patterns may be arbitrary. The DAD_PBD software can automatically identify and allocate the loads to their respective load combinations (See Section 2.4.3 for load combinations) provided that the load types are correctly defined.

It is also important to note that the current version of DAD_PBD does not support live load reduction. Although live load reduction is permitted under ASCE 7-22 (Section 4.7) [2], ETABS applies the live load reduction during the design phase. In contrast, DAD_PBD does not utilize the ETABS design tool, and the design capacity of each member is calculated independently. Live load reduction will be incorporated into future software updates.

Before launching the DAD_PBD software, it is advised to remove any wind load patterns or cases used in the preliminary design of the building. This practice can reduce computational time by preventing redundant calculations. Additionally, if the user plans to utilize the linear direct integration analysis for dynamic analysis, it is necessary to include a dummy load case in the load case list. Refer to Section 2.4.3 for further details.

The DAD_PBD provides three options to analyze the structural members for steel-frame building: 1) one frame element, 2) multiple frame elements, or 3) all members. For the second option, it is critical that the user assigns a “Group” to all frame elements of interest in the ETABS model. This step should be completed before starting the DAD_PBD software because the software makes multiple copies of the ETABS models and transfers the “Group” information through the DAD process. Refer to Section 2.6 for an example.

2.4. Getting Started

2.4.1. Initialization

To initiate the DAD_PBD, the user should execute the DAD_PBD.exe file, which is freely available for download in Database Assisted Designs Section 3 at www.nist.gov/wind. Once the software is launched, it will automatically search for and load the Python dll file (see Section 2.2 for Python installation). The typical directory for the Python dll file is in the following format:

‘C:\Users\Username\AppData\Local\Programs\Python\PythonXX\pythonXX.dll’,

where the XX indicates the Python version. For example, the directory of the Python version 3.8 dll file would be:

‘C:\Users\Username\AppData\Local\Programs\Python\Python38\python38.dll’.

If Python is installed in a different location and cannot be loaded, a pop-up window will appear, prompting the user to manually specify the directory for the Python dll file.

The DAD_PBD starts by selecting the structure type. Under the “**Type of Structure**” panel, the user must select “**Steel Structure**” for steel-framed buildings or “**Reinforced Concrete Structure**” for RC buildings. Note that some features will become available or unavailable depending on the type of structure. Further details are provided in Sections 2.6.1.1 and 2.6.1.2.

Next, the user must locate and load the ETABS model of the preliminary design (file with extension .edb) and the ETABS API dll file (ETABSv1.dll). The file paths can be browsed using the

"Browse" buttons in the "**Initialization**" tab (Fig. 3) or directly typed in. For convenience, the ETABS model stored in this directory will be termed the "base ETABS model" throughout this document. In a typical ETABS installation, the directory path to the ETABS API dll file is:

'C:\Program Files\Computers and Structures\ETABS XX\ETABSv1.dll',

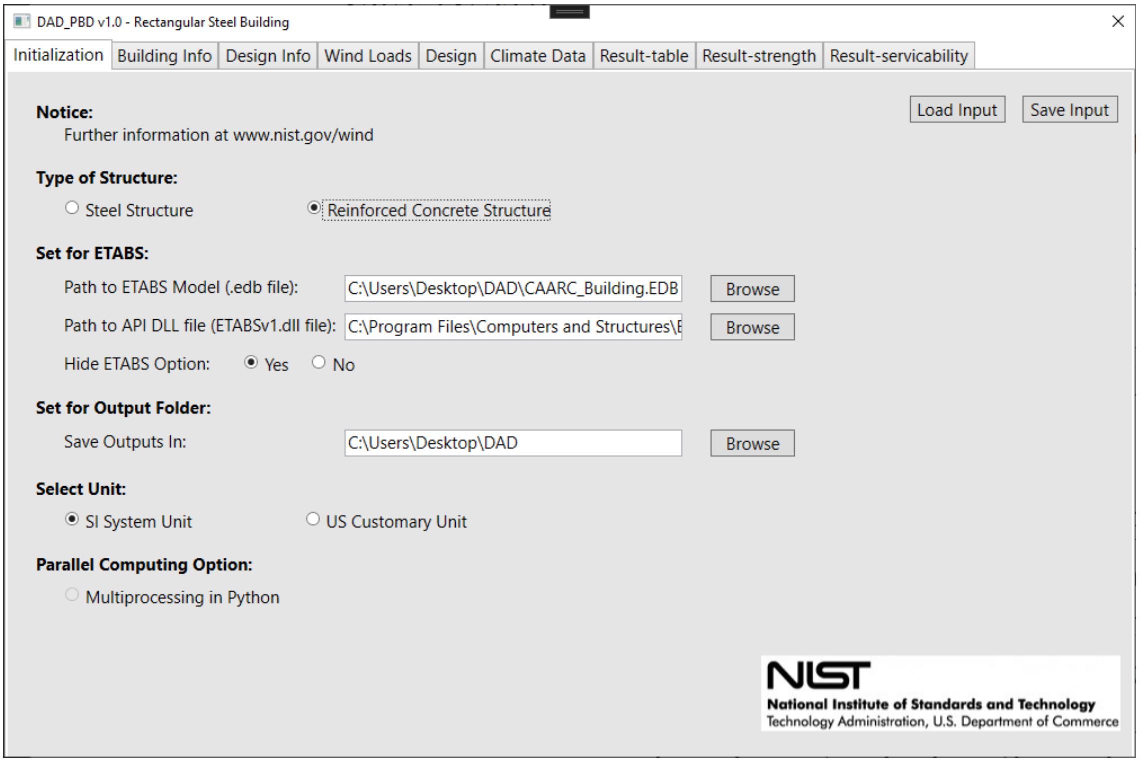
where the XX indicates the ETABS version. Clicking the "**Browse**" button under the "**Save Outputs In**" panel allows the user to select a folder path for storing all analysis outputs and figures. Note that altering or deleting any files or paths within this folder may cause errors, as the software depends on this directory to save and access the analysis results.

The user can choose to run the ETABS application in the background by choosing "**Yes**" under the "**Hide ETABS option**". This setting hides the ETABS GUI from the view throughout the entire DAD process and typically results in slightly faster computational processing.

The DAD_PBD supports two unit systems: SI units and US customary units. For force and length inputs, SI units use kilo-Newton or Newton (kN or N), while meter (m) and US customary units use 1000 pounds-force (kip) and feet (ft). All data saved after the analysis will be in Newton (N) and meter (m) for SI units, and pounds-force (lbf) and feet (ft) for US customary units. The CAARC building [24] example featured in this report uses SI units.

Note that the "**Multiprocessing in Python**" radio button under "**Parallel Computing Options**" is unavailable (indicated by being grayed out), as shown in Fig. 3. This feature is deemed unnecessary in the current version, as the matrix analyses in Python have already achieved a sufficient reduction in computational time. However, it may become necessary in future versions of DAD_PBD as more complicated procedures are implemented.

In the top right corner of each tab, two buttons are available for managing the input data: 1) "**Load Input**" and 2) "**Save Input**". The "**Save Input**" button stores any input data entered by the user in a text (.txt) file, prompting the user to select a folder to save and then type the name for the input data file. Note that the "**Save Input**" button effectively saves input for all tabs. Each line in the text file corresponds to a specific input, which the user can directly modify with the text file. Refer to Appendix C for the line correspondence. The "**Load Input**s" button retrieves and displays the input data. The functionality of these two buttons is consistent across all tabs. This feature helps track inputs during the redesign process or recover from unexpected interruptions. If the software encounters issues during an analysis, previously saved inputs can be retrieved with the "**Load Input**" button. It is advisable to save and create an input data file at each step or whenever changes are made. Note that the input data file (.txt) only includes the information entered into the software and does not include any analysis results.



DAD_PBD v1.0 - Rectangular Steel Building

Notice:
Further information at www.nist.gov/wind

Type of Structure:
○ Steel Structure ● Reinforced Concrete Structure

Set for ETABS:
Path to ETABS Model (.edb file): C:\Users\Desktop\DAD\CAARC_Building.EDB
Path to API DLL file (ETABSv1.dll file): C:\Program Files\Computers and Structures\E
Hide ETABS Option: ● Yes ○ No

Set for Output Folder:
Save Outputs In: C:\Users\Desktop\DAD

Select Unit:
● SI System Unit ○ US Customary Unit

Parallel Computing Option:
○ Multiprocessing in Python

Fig. 3. Initialization step of the graphical user interface of DAD_PBD.

2.4.2. Building Information

The geometry of the building must be entered in the "**Building Info**" tab before the software can calculate the wind loads. First, the building shape must be selected from the currently available types of shapes: 1) "Rectangular shape," 2) "Irregular shape." The "**Rectangular shape**" is defined as a prismatic building with a rectangular in-plan footprint, whereas the "**Irregular shape**" is defined as a prismatic building with four walls that vary linearly with height. For rectangular-shaped buildings, the user enters the width, depth, and height of the building, as well as the number of stories. The width and depth are defined as the horizontal length of the building along the x- and y-axes, respectively (Fig. 4). For the irregular-shaped buildings, the user enters the building widths and depths at the top and bottom, the height and the number of stories. The building geometry can be manually entered or imported directly from ETABS by clicking the "**Read ETABS**" button, which will open the basic ETABS model and automatically import the building information from ETABS.

Building offsets (e.g., "**X-offset**", "**Y-offset**") are necessary for the base ETABS model unless the origin (0,0) of the x-, y-coordinates are located in the center of the building geometry. These inputs are important for wind load calculations. See Section 2.5.1.2 for details.

The building orientation (α_0) is the clockwise angle from the true North to the positive x-direction of the building, as shown in Fig. 4. For instance, the orientation would be 90 degrees for a building whose positive x-axis (+) points toward the East. The orientation angle is critical for wind directionality analysis and must be entered manually. The wind direction (θ) is defined as the angle at which the wind approaches the building and increases clockwise from the x-axis (See Fig. 4).

The features under "**Modal Analysis**" panel (e.g., number of modes, natural frequencies, and damping ratio) are currently unavailable; thus, they are grayed out in Fig. 5. This module, which can offer users insights into the structural dynamic properties of the building, will be available in future software versions.

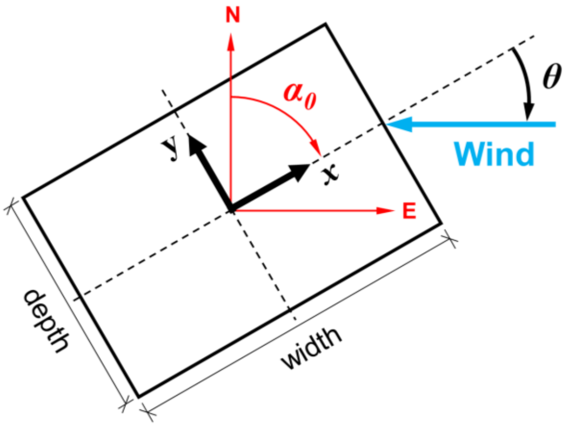
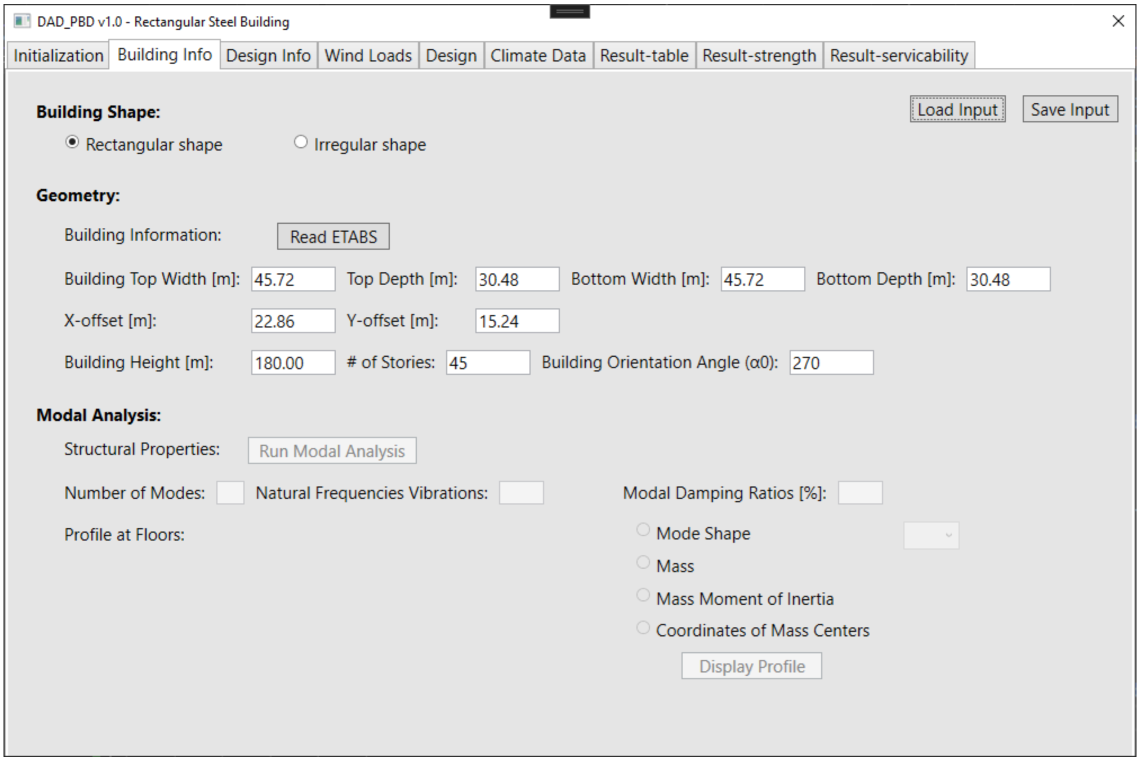


Fig. 4. Plan view of the building showing orientation angle and wind direction.



Building Shape:
● Rectangular shape ○ Irregular shape

Geometry:
Building Information:
Building Top Width [m]: 45.72 Top Depth [m]: 30.48 Bottom Width [m]: 45.72 Bottom Depth [m]: 30.48
X-offset [m]: 22.86 Y-offset [m]: 15.24
Building Height [m]: 180.00 # of Stories: 45 Building Orientation Angle (α0): 270

Modal Analysis:
Structural Properties:
Number of Modes: Natural Frequencies Vibrations: Modal Damping Ratios [%]:
Profile at Floors:
○ Mode Shape
○ Mass
○ Mass Moment of Inertia
○ Coordinates of Mass Centers

Fig. 5. DAD_PBD building information input window.

2.4.3. Design Information

In the "**Design Info**" tab, the user needs to select the analysis type and enter the load combinations. Begin by choosing the preferred structural and dynamic analysis type of the ETABS model. The "**Analysis Type**" drop-down menu offers the following six types of analysis:

1. *Linear Modal Time-History w/o P-Delta*
2. *Linear Modal Time-History w/ Pseudo P-Delta*: equivalent to Linear Modal Analysis with preset P-Delta in ETABS. The P-Delta effect is taken into account using the softened stiffness.
3. *Non-Linear Modal Time-History w/ Pseudo P-Delta*: equivalent to Nonlinear Modal Analysis (FNA) with consideration of P-Delta in ETABS. The P-Delta effect is included using the softened stiffness of a nonlinear static load case.
4. *Linear Direct Time-History w/ Pseudo P-Delta*: equivalent to Linear Direct Integration with preset P-Delta in ETABS. The P-Delta effect is taken into account using the softened stiffness.
5. *Non-Linear Direct Time-History w/ Pseudo P-Delta*: equivalent to Nonlinear Direct Integration using the initial condition of "Continue from State at End of Nonlinear Case" in ETABS. The P-Delta effect is included using the softened stiffness of a nonlinear static load case.
6. *Non-Linear Direct Time-History w/ Concurrent P-Delta*: equivalent to Nonlinear Direct Integration with zero initial conditions (start from the unstressed state) in ETABS. In this load case, the P-Delta effect is taken into account using the stiffness in the concurrent time step.

The currently available analysis types are the Linear Modal Time History analysis without P-Delta (Option 1), the Linear Modal Time History analysis with pseudo P-Delta (Option 2), and the Linear Direct Integration Time History analysis with pseudo P-Delta (Option 4). The current DAD_PBD does not offer the non-linear analysis option, which is a critical component of PBD. However, future versions of DAD_PBD will introduce a DAD design procedure that incorporates both geometric and material non-linearities, along with the non-linear analysis options.

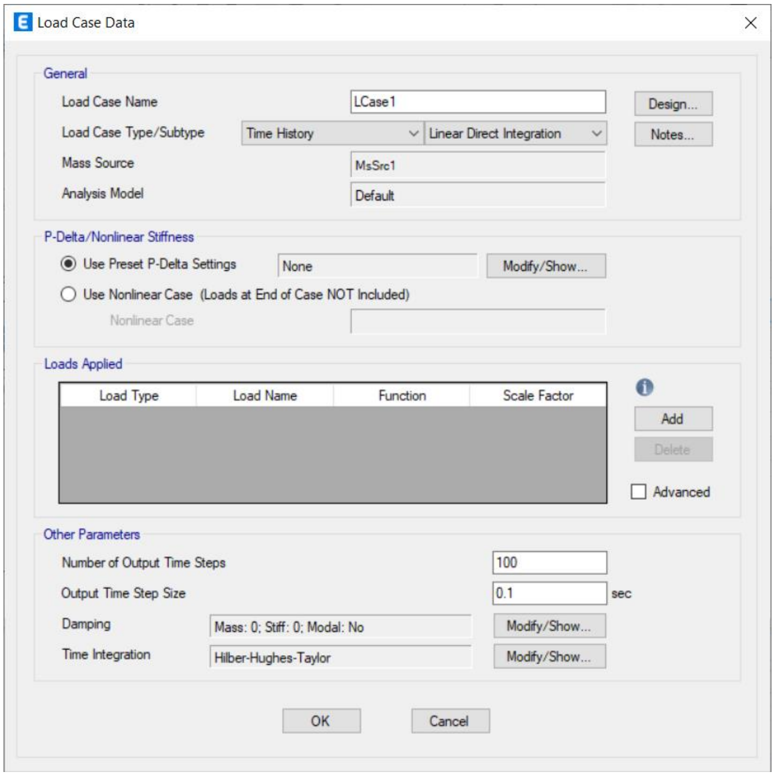
When the user employs the fourth option (i.e., Linear Direct Time-History Analysis w/ Pseudo P-Delta), a "dummy" load case with Linear Direct Integration must be added to the basic ETABS model due to limitations in the current ETABS API's functionality. This step populates a Time History Load Case Definition with Linear Direct Integration in the ETABS table. Once the load case is populated, the API function can be used to manipulate the load case. Thus, no further modification of settings, other than shown in Fig. 6(a), is necessary. This step may become unnecessary as future ETABS versions are updated. An example of adding a dummy load case named "LCase1" is shown in Fig. 6.

If the analysis type with the pseudo P-Delta option is chosen, the user must define the dead load (DL) and live load (LL) cases used for the softened stiffness under the "**P-Delta Presets**" panel. For example, the P-Delta preset is set to “1.2*D* + 1.0*L*” for the DL and LL values shown in Fig. 7.

Additionally, the user should specify the desired load combinations for the structural/dynamic analysis. If the load combinations are already defined in the basic ETABS model, they can be imported by clicking the “**Import ETABS Load Combinations**” button. Alternatively, the user can manually create a list of load combinations by entering the load factors and clicking the “**Add**” button. For instance, the load factors shown in Fig. 7 will produce load combinations for strength and serviceability designs as follows:

- Strength Design: 1.2*DL* + 1.0*LL* + 1.0*WL*
- Serviceability Design: 1.0*DL* + 0.5*LL* + 1.0*WL*

where *DL* is the dead load, *LL* is the live load, and *WL* is the wind load. For load cases with no applied loads, 0 must be entered for those loads. For example, to add a load case of 0.9*DL* + 1.0*WL*, the user should enter 0.9 for the dead load, 0 for the live load, and 1 for the wind load. To clear all load combinations, click the “**Clear**” button, and to remove a specific load combination, choose the load combination to remove and click the “**Delete**” button.

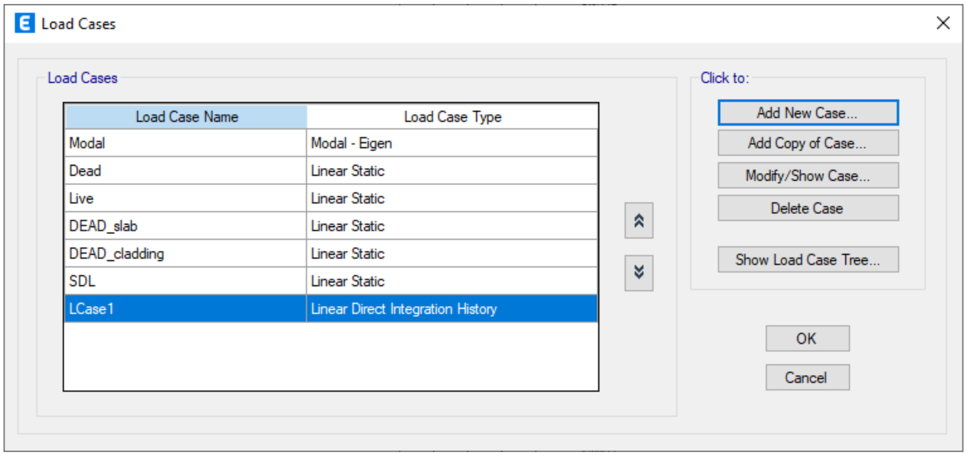


Load Case Name: LCase1
Load Case Type/Subtype: Time History; Linear Direct Integration
Mass Source: MsSrc1
Analysis Model: Default
● Use Preset P-Delta Settings: None
○ Use Nonlinear Case (Loads at End of Case NOT Included)
Nonlinear Case:

Load Type	Load Name	Function	Scale Factor

☐ Advanced
Number of Output Time Steps: 100
Output Time Step Size: 0.1 sec
Damping: Mass: 0; Stiff: 0; Modal: No
Time Integration: Hilber-Hughes-Taylor

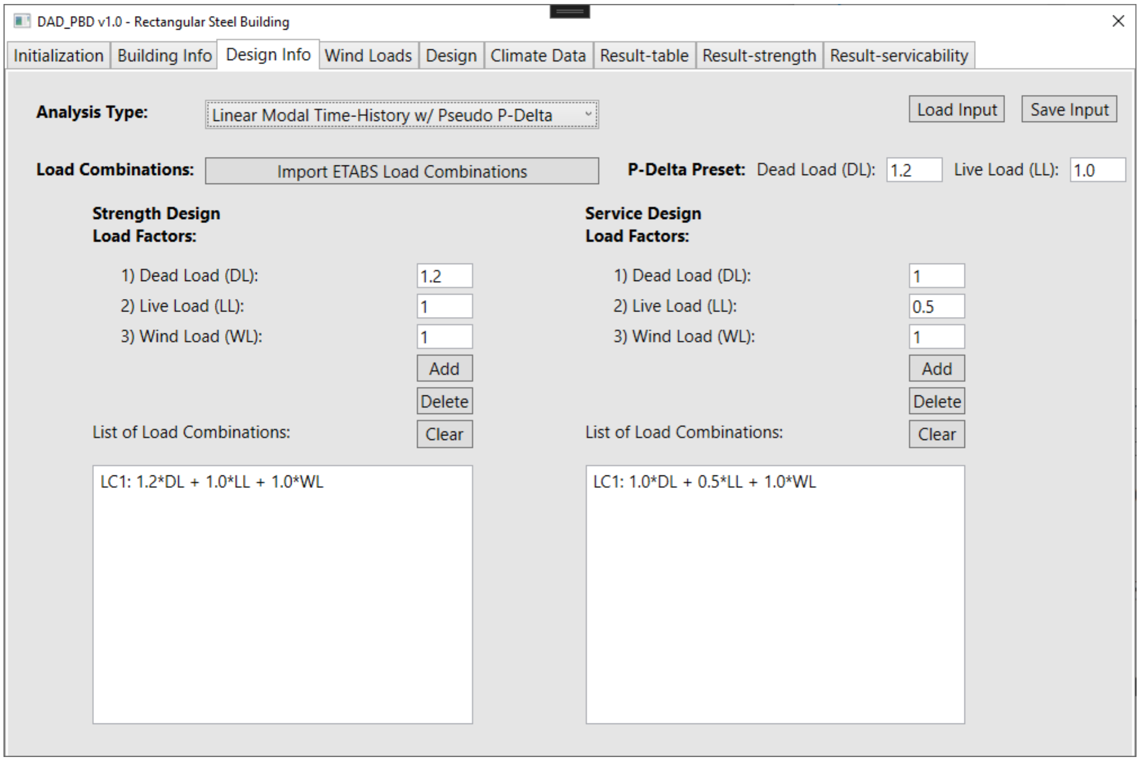
(a) ETABS Load Case Data window for adding the “dummy” Time History Linear Direct Integration load case



Load Case Name	Load Case Type
Modal	Modal - Eigen
Dead	Linear Static
Live	Linear Static
DEAD_slab	Linear Static
DEAD_cladding	Linear Static
SDL	Linear Static
LCase1	Linear Direct Integration History

(b) ETABS Load Cases window after adding the “dummy” load case

Fig. 6. Demonstration of adding a “dummy” load case in ETABS for the Linear Direct Time-History w/ Pseudo P-Delta analysis.



Analysis Type: Linear Modal Time-History w/ Pseudo P-Delta

Load Combinations:

P-Delta Preset: Dead Load (DL): 1.2 Live Load (LL): 1.0

Strength Design Load Factors:

1) Dead Load (DL): 1.2
2) Live Load (LL): 1
3) Wind Load (WL): 1

List of Load Combinations:

LC1: 1.2*DL + 1.0*LL + 1.0*WL

Service Design Load Factors:

1) Dead Load (DL): 1
2) Live Load (LL): 0.5
3) Wind Load (WL): 1

List of Load Combinations:

LC1: 1.0*DL + 0.5*LL + 1.0*WL

Fig. 7. DAD_PBD design information and load combinations input window.

2.5. Wind Load Calculation

For the calculation of wind loads on dynamically sensitive or irregular-shaped buildings, DAD_PBD requires a time series of aerodynamic pressure data measured simultaneously at multiple pressure taps on a building model at various wind directions (θ in Fig. 4). Recent advancements in CFD techniques and computer technology have considerably enhanced the ability to produce such aerodynamic pressure data on buildings [8]. The pressure data from CFD simulations can be used to estimate wind loads on a building, *provided that the numerical method is verified and validated*, as outlined in ASCE 7-22 Section 31.1 [2].

In general, pressures are represented using non-dimensional pressure coefficients, C_p, defined as follows:

$$C_p = \frac{p - p_{ref}}{\frac{1}{2}\rho V_m^2} \tag{1}$$

where p is the absolute pressure measurement at each pressure tap, p_{ref} is the reference pressure measured away from the building, ρ is the air density, and V_m is the reference mean velocity at the roof height of the building.

To accurately apply the experimental wind loads to the full-scale ETABS building model, the full-scale time step and applied loads must be accurately calculated using the similarity of the non-dimensional scales between the full-scale building and the wind tunnel model. The non-dimensional scales include length scale factor (K_L), time scale factor (K_T), and velocity scale factor (K_V), as expressed in Eqs. (2-4).

$$K_L = \frac{D_m}{D_f} \tag{2}$$

$$K_T = \frac{\Delta t_m}{\Delta t_f} \tag{3}$$

$$K_V = \frac{V_m}{V_f} \tag{4}$$

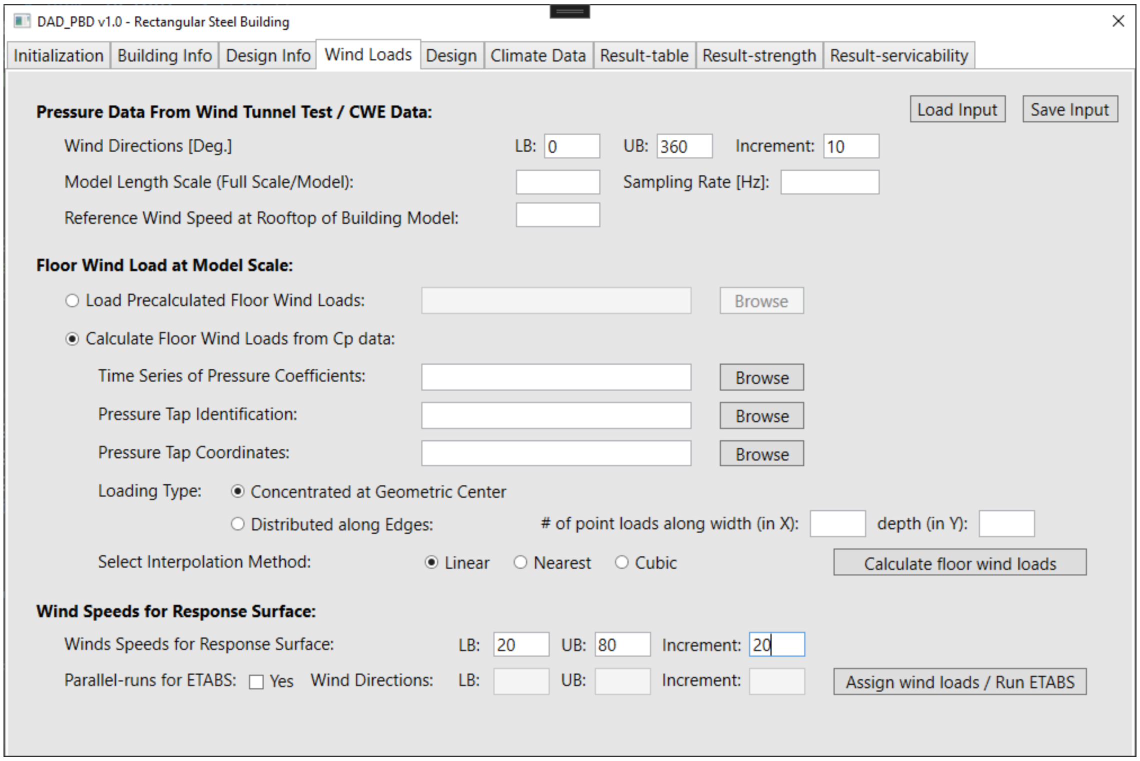
where D, Δt, and V represent the reference length, reference time step, and reference velocity, respectively. The subscripts m and f denote the model-scale and full-scale tests, respectively. By substituting the non-dimensional scales (Eqs. 2-4) into the law of dynamic similarity ($K_V = K_L/K_T$), the full-scale time step, Δt_f, can be expressed as shown in Eq. (5). Additionally, the force scale factor (K_F) and moment scale factor (K_M) can be determined using Eqs. (6) and (7), respectively. With the non-dimensional scales provided, these scale factors are computed and automatically applied to the ETABS building model for the dynamic analysis.

$$\Delta t_f = \frac{K_V}{K_L}\Delta t_m = \frac{D_f}{D_m}\frac{V_m}{V_f}\Delta t_m \tag{5}$$

$$K_F = \left(\frac{1}{K_V}\right)^2\left(\frac{1}{K_L}\right)^2 = \left(\frac{V_f}{V_m}\right)^2\left(\frac{D_f}{D_m}\right)^2 \tag{6}$$

$$K_M = \left(\frac{1}{K_V}\right)^2 \left(\frac{1}{K_L}\right)^3 = \left(\frac{V_f}{V_m}\right)^2 \left(\frac{D_f}{D_m}\right)^3 \tag{7}$$

Under the “**Wind Loads**” tab in Fig. 8, the user is prompted to enter the specific details of the wind tunnel provided by the wind engineer, along with other necessary information for calculating the floor wind loads. As shown in the figure, the required details include the length scale, the reference mean wind speed at the roof height (V_m), the sampling rate (unit in hertz) of the C_p data, and the wind directions (θ) relative to the building orientation (refer to Fig. 4). Note that the software input for the length scale is the reciprocal of K_L. For example, K_L of 1/500 should be entered as 500 for the length scale input. The wind direction range can be specified using the lower bound (LB) and upper bound (UB) wind directions and their increment. For instance, the input shown in Fig. 8 generates wind direction of 0, 10, 20, ..., 350, and 360 degrees. A broad range and high resolution of wind speed and direction are essential for accurately estimating the building response and the effects of local wind climates. In general, the increments for both wind speeds and directions are advised not to exceed 10 m/s and 10 degrees, respectively. Note that wind direction entries (e.g., LB, UB, increment) must be integers.



Pressure Data From Wind Tunnel Test / CWE Data:
Wind Directions [Deg.] LB: 0 UB: 360 Increment: 10
Model Length Scale (Full Scale/Model):
Sampling Rate [Hz]:
Reference Wind Speed at Rooftop of Building Model:

Floor Wind Load at Model Scale:
○ Load Precalculated Floor Wind Loads:
● Calculate Floor Wind Loads from Cp data:
Time Series of Pressure Coefficients:
Pressure Tap Identification:
Pressure Tap Coordinates:
Loading Type: ● Concentrated at Geometric Center
○ Distributed along Edges: # of point loads along width (in X): depth (in Y):
Select Interpolation Method: ● Linear ○ Nearest ○ Cubic

Wind Speeds for Response Surface:
Winds Speeds for Response Surface: LB: 20 UB: 80 Increment: 20
Parallel-runs for ETABS: ☐ Yes Wind Directions: LB: UB: Increment:

Fig. 8. DAD_PBD “Wind Loads” tab for loading files and input parameters.

There are two options for loading the time-history wind load data to the DAD_PBD. The user can import either:

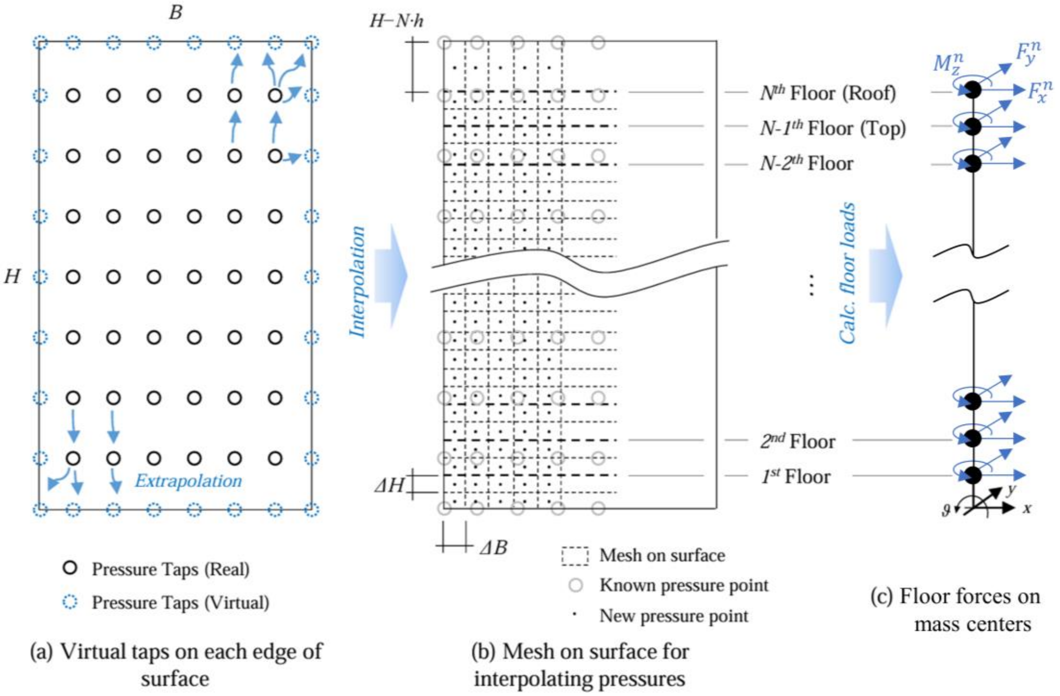
- the precalculated floor wind loads, or
- the C_p data only and let the software calculate the floor loads.

If the user has obtained the floor load time histories from the wind engineer, they can choose the first option by selecting the “**Load Precalculated Floor Loads**” button, bypassing the wind load calculations in the software. For the second option, the user must select the “**Calculate Floor Wind Loads from Cp data**” button, upload metadata for the pressure taps (including tap identification and coordinates), and specify the folder directory for saving the calculated floor wind loads and defining the number of data points. The wind load calculation can then be initiated by pressing the “**Calculate floor wind loads**” button. Data files can be located and loaded using the “**Browse**” buttons. Detailed descriptions of data formats for floor wind loads, C_p data, and pressure tap information are available in Appendix A.

For assigning the floor wind loads to the ETABS building model, the DAD_PBD software offers two options: 1) concentrated floor loads at the floor geometric center and 2) distributed floor loads along the floor edges. Under the “**Loading Type**”, the users must select the “**Concentrated at Geometric Center**” button or the “**Distributed along Edges**” button. The first option assigns three wind loads for each floor (two translational loads in the principal X and Y axes and one torsional load along the Z axis) at the floor’s geometric center, making it suitable for rectangular-shaped buildings. The second option, newly developed in the version, assigns discretely distributed loads along the floor edges, which is applicable to both regular- and irregular-shaped buildings. This distributed wind load option also effectively evaluates the structural response of buildings with asymmetric lateral load resisting systems along their height, such as rectangular-shaped buildings with eccentric shear wall structural systems.

2.5.1. Rectangular-Shaped Building

DAD_PBD employs an interpolation scheme to create “virtual taps” to calculate the floor wind loads on rectangular-shaped buildings. Figure 9 illustrates the interpolation scheme used in DAD_PMD. The outermost pressure taps are first extrapolated to the edge of the building, and then the pressures on the “virtual taps” are estimated through the nearest extrapolation. The pressures on systematically generated pressure points are obtained from the interpolation of those on both the extrapolated and actual pressure taps. The floor wind loads are then calculated from the pressure data consistently distributed over the building surface. Note that the DAD_PBD provides nearest, linear, and cubic interpolation methods, as shown in Fig. 9. Details on calculating the floor wind loads from wind tunnel pressure data are provided in [25].



(a) Virtual taps on each edge of surface

(b) Mesh on surface for interpolating pressures

(c) Floor forces on mass centers

Fig. 9. Illustration of interpolation scheme and mesh on the model surface. Image modified from [25].

2.5.1.1. Concentrated Loads at Floor Geometric Center

For the assignment of the concentrated loads to floor geometric centers, “virtual taps” are positioned at intervals of ΔB $(B/2n_B)$ along the length and ΔH $(H/2N)$ along the height, where B is the length (width or depth), H is the height of the modeled building, N is the number of floors, and n_B is the number of the virtual pressure taps per row. This method is currently only applicable to buildings with uniform height across all floors. Future software versions will address this limitation, allowing users to design buildings with varying story heights.

The floor wind loads are then calculated using the pressure at the virtual taps and their tributary areas and applied to the geometric center of the floor slab on each floor, as illustrated in Fig. 10. The time history wind loads on the floor geometric centers consist of translational forces along the principal axes of the structure (F_x, F_y) and a torsional moment about the geometric center (M_z). The mathematical formulations for these loads are given in Eqs. (8-10):

$$F_x^n(t) = \frac{1}{2}\rho V_m^2 \sum_i \left(C_{p,i}^{n-1}(t) A_{T,i}^{n-1} + C_{p,i}^{n}(t) A_{T,i}^{n} \right) \tag{8}$$

$$F_y^n(t) = \frac{1}{2}\rho V_m^2 \sum_i \left(C_{p,j}^{n-1}(t) A_{T,j}^{n-1} + C_{p,j}^{n}(t) A_{T,j}^{n} \right) \tag{9}$$

$$M_z^n(t) = \frac{1}{2}\rho V_m^2 \left(\sum_i \left(C_{p,i}^{n-1}(t) A_{T,i}^{n-1} + C_{p,i}^{n}(t) A_{T,i}^{n} \right) d_i + \sum_i \left(C_{p,j}^{n-1}(t) A_{T,j}^{n-1} + C_{p,j}^{n}(t) A_{T,j}^{n} \right) d_j \right) \tag{10}$$

where A_T represents the tributary area ($\Delta B \times \Delta H$); d represents the moment arm (projected distance) from the tap to the floor geometric center; the subscripts i and j represent the i^{th} pressure point on the building surfaces parallel to the x-axis and j^{th} pressure points parallel to the y-axis, respectively; and the superscript n represents the n^{th} floor. For reference, C_p^n and A_T^n are defined as pressure taps and tributary areas right above the floor. Note that the floor loads are calculated using the pressure taps and tributary area above (C_p^n and A_T^n) and below (C_p^{n-1} and A_T^{n-1}) the n^{th} floor, and the ground-level floor loads (GF_x, GF_y, GM_z) and the top floor (N^{th} floor) loads are calculated for foundation design using only the bottom-most and top-most tributary areas, respectively.

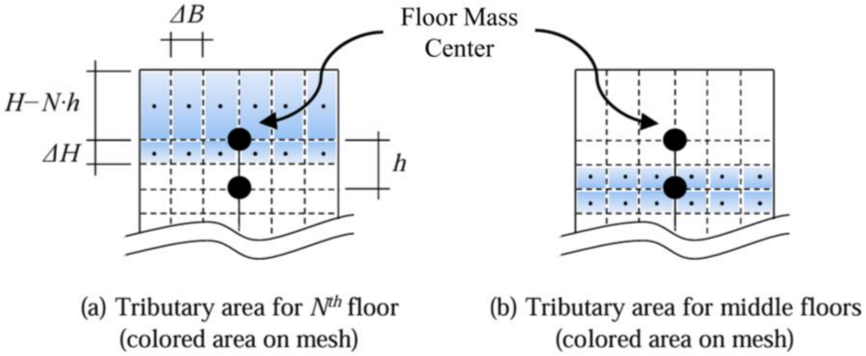


Fig. 10. Illustration of tributary area and floor loads calculation. Image modified from [25].

2.5.1.2. Distributed Loads along Floor Edges

For the assignment of discretely distributed loads along floor edges, multiple point loads are distributed at uniform intervals along the edges of the floor. The user is prompted to enter the number of point loads along the width and depth of the building (i.e., in the x- and y-directions, respectively). “Virtual taps” are then created at equal distances based on the number of point loads, and their pressures are interpolated from those on the extrapolated and the actual pressure taps (see Fig. 9). In the “**Wind Loads**” tab (Fig. 8), the user specifies the numbers of point loads along the building’s width (x-axis) and depth (y-axis) under the fields **“# of point loads along width (in X)**” and “**depth (in Y)**”, respectively. The horizontal interval along the length is calculated as $\Delta B = B/N_B$, where N_B denotes the number of point loads defined by the user. Note that N_B can be chosen differently depending on the width and depth of the building. The mathematical formulations of point loads along the building width and depth are expressed in Eqs. (11-12):

$$F_{x,k,i}^{n}(t) = \frac{1}{2}\rho V_m^2 \left(C_{p,i}^{n-1}(t) A_{T,i}^{n-1} + C_{p,i}^{n}(t) A_{T,i}^{n} \right) \tag{11}$$

$$F_{y,k,j}^{n}(t) = \frac{1}{2}\rho V_m^2 \left(C_{p,j}^{n-1}(t) A_{T,j}^{n-1} + C_{p,j}^{n}(t) A_{T,j}^{n} \right) \tag{12}$$

where A_T is now $B/N_B \times \Delta H$; F_x and F_y represent the point loads in the x- and y-directions, respectively. The subscripts i and j represent the i^{th} point load on the building surfaces parallel to the x-axis and the j^{th} point load parallel to the y-axis, respectively; the subscripts k represents the wall face number (See Fig. 11); and the superscript n represents the n^{th} floor. Note that the point number increases from left to right and bottom to top, following the x-y coordinate system order. Note that the torsional moment is not employed for this distributed loading option since the effects of wind-induced torsions on the building can be captured by the distributed translational loads applied to the building façade. Figure 11 illustrates an example of five distributed point loads in both x- and y-directions applied to the edges of the n^{th} floor of the CAARC building. Additionally, the ground-level distributed floor loads ($GF_{x,k,i}$, $GF_{y,k,i}$) are applied to the ground level to calculate the wind-induced effective wind loads for foundation design. Note that this method only applies to buildings with uniform height across all floors.

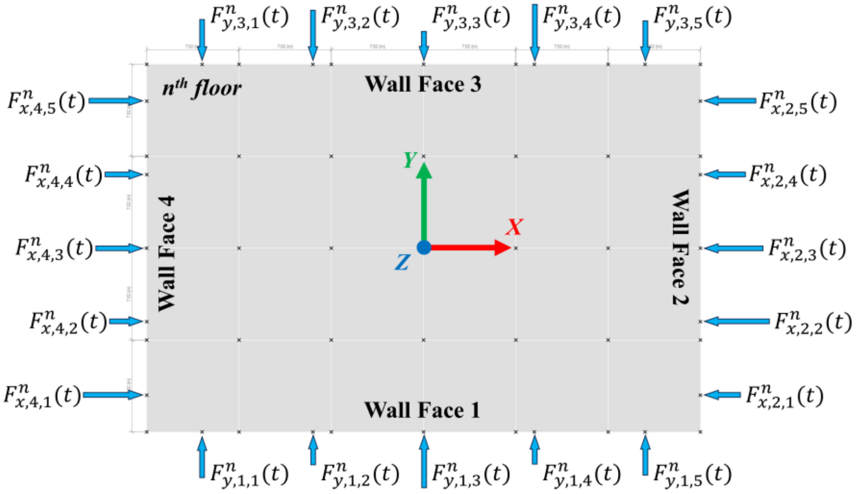


Fig. 11. Illustration of geometry-centered loads and distributed point loads on the *n*th floor.

It is important to note that ETABS has a limitation on the number of point loads that can be applied to buildings for time history analysis. If the limit is exceeded, ETABS produces an error in the time history analysis. This limitation may be due to the current capabilities of the ETABS software, which could be improved in future versions. The allowable number of distributed point loads depends on a combination of factors, such as the number of stories, the number of timesteps in the wind tunnel time history, and the computer RAM. For example, it was observed that the maximum allowable number of point loads was five points for both x- and y-directions on a 64GB Random-Access Memory (RAM) desktop PC computer with wind tunnel pressure data of 7504 timesteps for a 45-story building. In ETABS versions up to 21, if a sufficient number of point loads cannot be applied to the building, the user is advised to choose the concentrated load option instead.

If the geometric center of the base ETABS model is not located on the origin (0,0) of the x- and y-coordinates, the user must enter the building offsets. Those offset values are used to correctly identify the coordinates of the distributed point loads on building edges. For example, if the origin of the RC building is located at the bottom left corner of the building, the offset values would be 22.86 m for the "**X-offset**" and 15.24 m for the "**Y-offset**". Conversely, if the origin is positioned at the top right corner, the offset values would be negative. If no offsets are entered, the software assumes that there are no offsets.

2.5.2. Irregular Shape Building

The developments of DAD_PBD have taken their first step in broadening its application to irregular-shaped buildings. However, the current version of the software has a limitation in the geometry of the irregular-shaped buildings that are rectangular in plan and vary linearly in height with four wall faces (i.e., any rectangular shape in plan and trapezoidal shape in elevation). Future DAD_PBD versions will address more complex shapes of irregular-shaped buildings.

For trapezoid-shaped buildings, the current version of DAD_PBD employs the interpolation scheme described in Section 2.5.1.2 with additional internal virtual taps (if needed) and transformation of building wall shapes. Before applying the interpolation scheme to the building walls, the number of pressure taps in each horizontal layer should be consistent over the building height, as shown in Fig. 9(a). If this is not the case, the software creates additional virtual pressure taps to ensure consistency in the tap layout. The trapezoidal shape of the wall, including the tap layout on it, is then transformed into a rectangular wall whose width is identical to the larger width of the trapezoidal wall. The interpolation scheme is applied to the pressures at the transformed pressure tap locations on the rectangular-shaped wall, as described in Section 2.5.1. The multiple distributed point loads, calculated from the pressures at the interpolated "virtual" taps and their tributary areas on the trapezoidal wall, are applied at equal distances along the edges of the floor.

For illustration purposes, this section uses a tapered building as an example. The aerodynamic pressure data of the tapered building was sourced from the Wind Engineering Information Center's TPU Aerodynamic Database [5]. Figure 12(a) illustrates a three-dimensional AutoCAD drawing of the tapered building model. To integrate with the DAD_PBD process, the TPU pressure data was modified by adding four "virtual" interpolated pressure taps (highlighted by orange circles in Fig. 12) on the top two rows of each wall. This adjustment creates a 10-by-5 pressure tap configuration for the respective wall. Further details on the pressure tap layout on a wall are provided in Appendix A.3. Figures 12(b) and (c) show the projected wall face of Wall Face 1 before and after the transformation. In this transformation, the edges of the tapered building wall are extended outward to form a rectangular shape. The pressure taps along the width are also proportionately extended, as shown in Fig. 12(b). Following the transformation, "virtual" taps at equal distances are created and interpolated in the same manner as described in Section 2.5.1.2. Note that the user specifies the number of point loads in the x- and y-direction (Fig. 8). After the interpolation, the "virtual" tap locations are transformed back to their original positions on the trapezoidal-shaped wall to calculate their trapezoidal tributary areas.

The mathematical formulations of the trapezoidal tributary area and the corresponding point load are provided in Eqs. (13) and (14), respectively:

$$A_{T,i}^{n} = \frac{(L_{n-1}/N_B + L_n/N_B)}{2} \times \Delta H = \frac{(L_{n-1} + L_n)}{2N_B} \Delta H \tag{13}$$

$$F^{n}_{R,k,i}(t)=\frac{1}{2}\rho V_m{}^{2}C^{n}_{p,i}(t)A^{n}_{T,i} \tag{14}$$

where L_n and L_{n-1} are the length (i.e., width for Wall Face 1 and 3 and depth for Wall Face 2 and 4) of the one-half above and below the n^{th} floor, respectively.

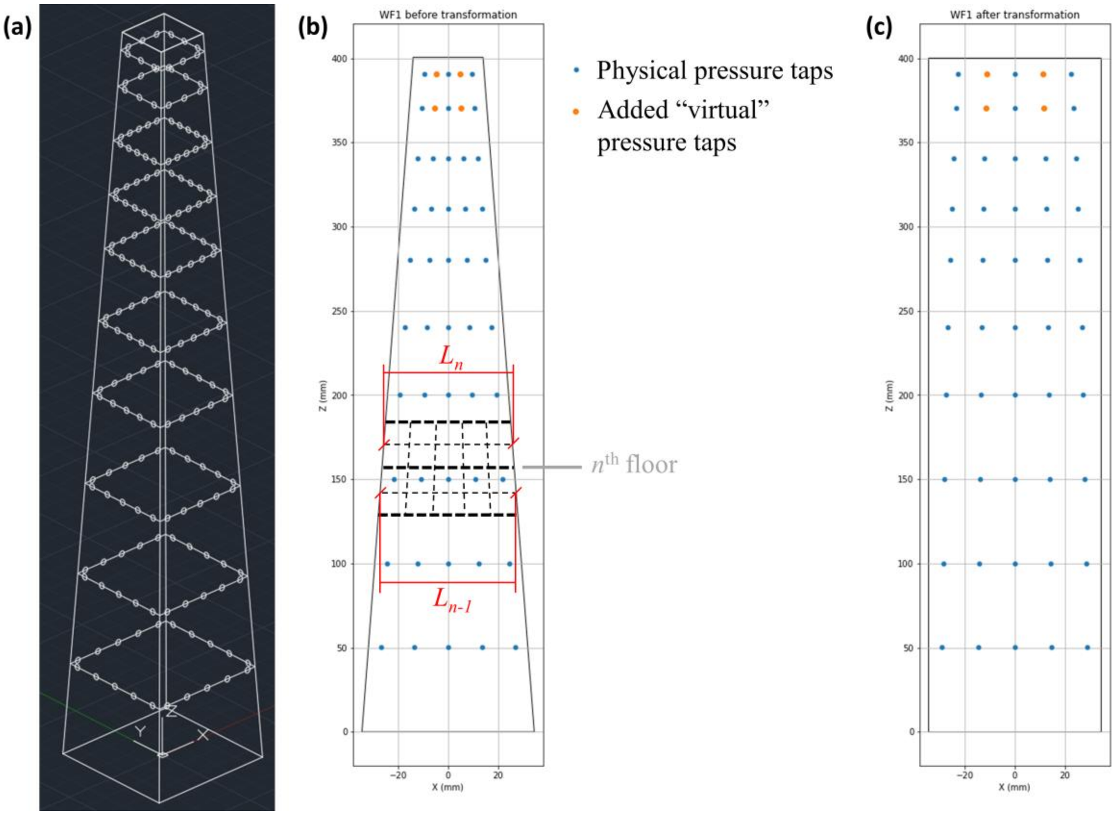


Fig. 12. Illustration of pressure tap transformation of the TPU tapered building: (a) 3D view in AutoCAD, (b) pressure tap location before transformation, (c) pressure tap location after transformation.

In addition, due to the sloped surfaces of the tapered building, the point loads are no longer confined to the principal directions. Instead, they are represented as resultant loads, F_R, (i.e., vector summation of F_x, F_y, and F_z), normal to the surface. In ETABS, oblique forces are represented by their components in the x-, y-, and z-directions. Consequently, the resultant loads, F_R, must be decomposed into three point load components in the three directions (F_x, F_y, and F_z). The magnitude of each decomposed load is calculated using the inner product of the magnitude of the resultant load and the normalized perpendicular-to-surface vector (n_1, n_2, n_3), as described in Eqs. (15-17). Note that the normal vector herein is defined as the vector pointing towards the building. Figure 13 shows a schematic presentation of the decomposed point loads applied to the building surface.

$$F^{n}_{x,k,i}(t)=\frac{1}{2}\rho V_m{}^{2}C^{n}_{p,i}(t)A^{n}_{T,i}n_1 \tag{15}$$

$$F^n_{y,k,i}(t) = \frac{1}{2}\rho {V_m}^2 C^n_{p,i}(t) A^n_{T,i} n_2 \tag{16}$$

$$F^n_{z,k,i}(t) = \frac{1}{2}\rho {V_m}^2 C^n_{p,i}(t) A^n_{T,i} n_3 \tag{17}$$

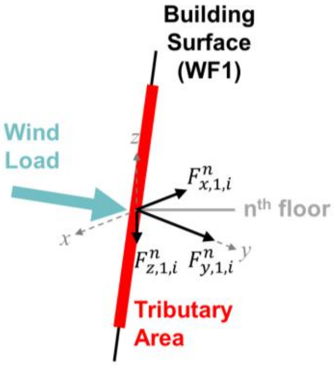


Fig. 13. Schematic drawing of the decomposed point loads applied to the building surface.

2.5.3. Floor Load Output

After completing the wind load calculation, an *"Output"* folder will be created in the directory specified by the user in the "**Save Outputs In**" textbox (refer to Fig. 3). The folder contains an HDF5 file named *"forces.hdf5"*, which includes the two principal wind forces and torsional moments for all floors (including the ground floor) under the concentrated load option, and the discretely distributed loads along the edges of all floors under the distributed load option. It also includes the user-input parameters. Additionally, a subfolder titled *"Floor_loads"* will be generated within the "*Output*" folder. The *"Floor_loads"* folder includes a series of folders with CSV files of the floor loads, which are used for assigning wind loads to the ETABS model. The organization of the folders and files adheres to a specific format:

- Folder: The folder name format adheres to *"WD_XXX"*, where *"XXX"* is the three-digit wind direction. For example, the folder containing the floor wind loads for 40-degree wind direction is written as *"WD_040"*.
- CSV Files for the concentrated loads: The CSV file format adheres to *"FYYY_XXX_Zz"*, where *"YYY"* is the three-digit floor number, *"XXX"* is the three-digit wind direction, and *Zz* corresponds to the load type (e.g., F_x, F_y, M_z). For ground floor loads, the format is *"GF_XXX_Zz"*. For example, the CSV files corresponding to the floor moments acting in the *z*-direction on the 18th floor for 320-degree wind direction and ground floor load in the x-direction for 270-degree wind direction are named *"F018_320_Mz.csv"* and *GF_270_Fx.csv*, respectively. Refer to Fig. 14(a) for an example.
- CSV Files for the distributed loads): The CSV file format adheres to *"FYYY_XXX_Zz_A_BB"*, where *"YYY"* is the three-digit floor number, *"XXX"* is the three-digit wind direction, *"Zz"* corresponds to the load type (e.g., F_x, F_y), *"A"* is the wall face number, and *"BB"* denotes

the point load number on each wall face. For ground floor loads, the format is *“GF_XXX_Zz_A_BB”*. For example, the CSV files of *“F018_320_Fx_4_5.csv”* and *“GF_270_Fy_1_2.csv”* correspond to the 5th floor point load on Wall Face 4 on the 18th floor for 320-degree wind direction and the 2nd ground-floor load acting on Wall Face 1 for 270-degree wind direction, respectively. For irregular-shaped buildings, the *“Zz”* will be replaced with just *“F”* for resultant loads. Refer to Fig. 14(b) for an example.

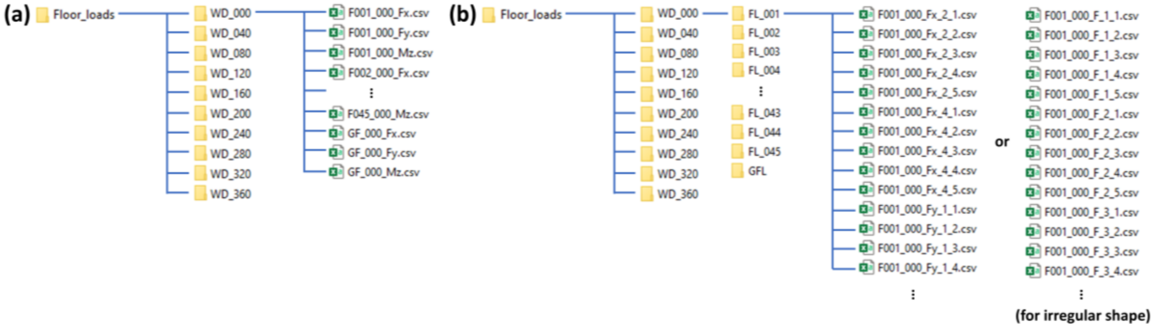


Fig. 14. Example list of folders and CSV files generated after wind load calculation: (a) concentrated loads method and (b) distributed loads method.

Upon completion of the wind load calculation, the wind speed range and its increment must be defined before advancing to the “**Design**” tab. The user must specify the wind speed range by inputting the lower bound (LB) and upper bound (UB) wind speeds and their increment. For example, the input values shown in Fig. 8 represent wind speeds of 20 m/s, 40 m/s, 60 m/s, and 80 m/s. When selecting the wind speed range and increment, it is important to balance accuracy and computational time. While the wind speed range may vary depending on the local wind climate of the building site, a common practice in DAD is to use wind speeds ranging from 20 m/s to 80 m/s with a 10 m/s increment. Note that all values for wind speed, including the LB, UB, and increment, must be entered as integers.

With the wind speed range for the response surfaces defined, the user can proceed to the assignment of the wind floor loads and execution of time history analyses on ETABS by clicking the “**Assign wind loads/Run ETABS**” button. At this stage, the software duplicates the base ETABS model for each wind direction. For each specified wind speed (e.g., 20 m/s, 30 m/s, ..., 80 m/s) and wind direction (e.g., 0 °, 10 °, …, 350 °), the software assigns the floor loads (i.e., the concentrated or distributed point loads) to the duplicated ETABS model and performs the ETABS analyses with the chosen analysis option (Section 2.4.3).

Upon completion of the analysis for each wind direction, a subfolder named *“Model_XXX”* is created within the *“ETABS_Model”* directory, where *“XXX”* denotes the three-digit wind direction. This subfolder contains all ETABS files associated with that specific wind direction. It is important to note that an ETABS model for 360 degrees wind direction is not generated, as the results are identical to those for 0 degrees. If the user inputs 0 degrees for the lower bound (LB) and 360 degrees for the upper bound (UB), the software will use the results from 0 degrees to represent those for 360 degrees in the response surface (refer to Section 2.6).

2.6. Response Surfaces of Design Parameters

Once the ETABS analyses are completed, the peak response of design parameters for each wind speed and direction are identified. These responses for all wind speeds and directions are then used to create their response surfaces, 3D contour maps depicting the relationship between wind speed and direction. The design parameters, including the Demand-to-Capacity Index (DCI), inter-story drift ratio, floor acceleration, and Deformation Damage Index (DDI), are outlined in the following subsections.

Within the "**Design**" tab (Fig. 15), the user must select the desired design parameters under the "**Design Parameters**" panel. Multiple design parameters can be chosen and analyzed simultaneously. Subsequently, the user is required to provide the following details.

1. For DCI, note that the procedure for selecting the members differs between steel-frame buildings and RC buildings. If "**DCI**" is chosen with "**Steel Structure**", the user must select "**Individual**", "**Group**", or "**All**" for steel-frame building. For the "**Individual**" or "**Group**" option, the user must enter the individual unique name (i.e., Unique Name in ETABS) or the group name (i.e., Selected Group in ETABS) of the structural members. The "**Individual**" option calculates the DCI of one selected member, whereas the "**Group**" option calculates the DCIs of multiple members simultaneously. For the "**All**" option, the unique name or the group name is not required, and the software will determine the DCI of all structural members within the ETABS model. Note that this option requires substantial computational resources and storage.

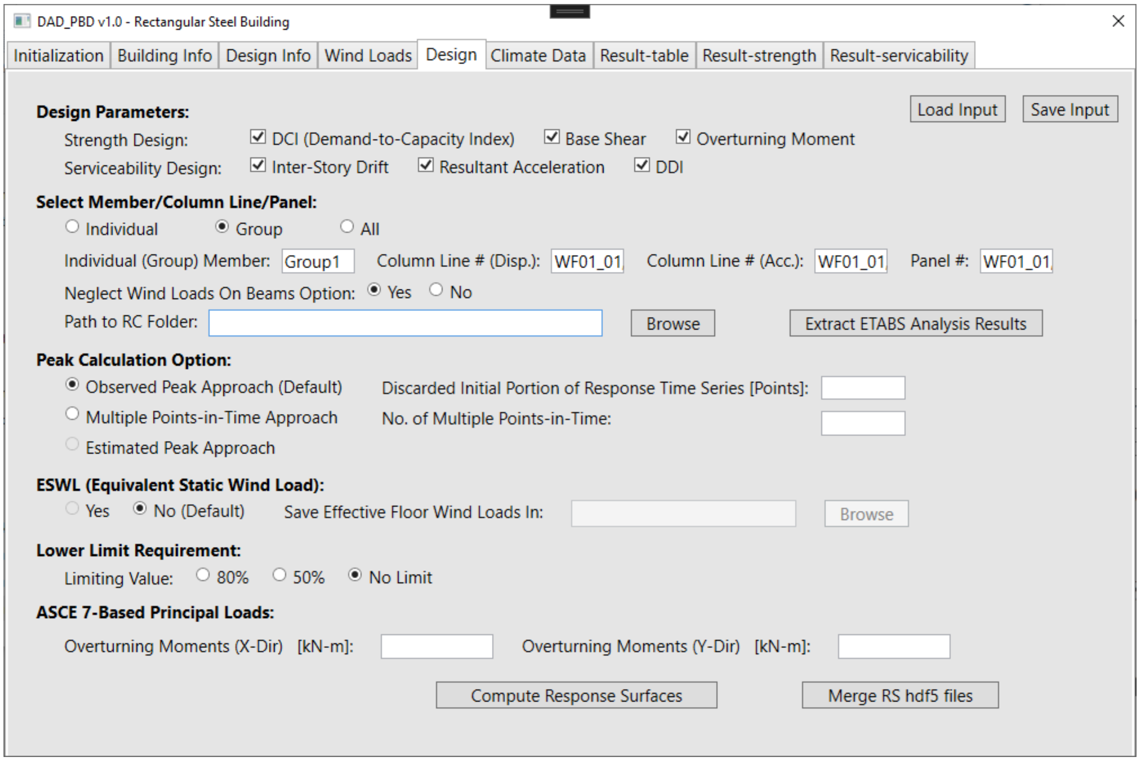
   For the "**Group**" option, the software relies on the "Group Definitions" feature in ETABS, which groups and assigns a group name to the selected frame elements. Before running the ETABS model, the group must be assigned in the base ETABS model to copy the group assignment to the duplicated ETABS models with the assigned wind loads. For guidance on defining and assigning members to a specific group, refer to the ETABS manual [15]. Ensure that only frame elements (e.g., columns, braces, beams) are included in the group to avoid errors. An example of group definition in the base ETABS model is shown in Fig. 16, where "Group1" (without quotation marks) is entered in Fig. 15, which calculates the DCIs of all frame elements in "Group1". Engineering judgment is necessary to determine whether the effects of wind loads on the beams can be neglected. The significance of wind effects on the beams depends on their location and connection. For beams designed as part of the lateral force-resisting system, their wind load effects should be taken into account. Otherwise, choose "**Yes**" under the "**Neglect Wind Loads on Beams Option**". In this case, the DCI of the beams becomes independent of time (see Section 2.6.1.1 for details), significantly reducing the computational runtime for the DCI calculation. Note that this option is only available for steel-framed buildings.

   If "**DCI**" is chosen with "**Reinforced Concrete Structure**", the user must upload Excel files (.xlsx) containing the member names and rebar schedule. The "**Path to RC folder**" is defined using the "**Browse**" button (see Fig. 15 to locate these Excel files. The DAD_PBD employs these Excel files, rather than ETABS, to identify the selected members. Consequently, the "**Individual**", "**Group**", and "**All**" buttons are ineffective if the

"**Reinforced Concrete Structure**" is selected in the "**Initialization**" tab. For more details on the Excel file with the rebar schedule for RC buildings, refer to Section 2.6.1.2.

2. If "**Inter-Story Drift**" is selected, enter the column line index (or indices) in the "**Column Line # (Disp.)**" box in Fig. 15 (see Fig. 17 for column line index) for which the inter-story drift ratios are to be determined. To analyze multiple column lines at once, type "WF01_01,WF02_2" (without quotation marks), for example, with commas in between the indices of the column line. Enter "All" or "all" (without quotation marks) to determine the inter-story drift ratios of all column lines.
3. If "**Resultant Acceleration**" is chosen, enter the column line index (or indices) in the "**Column Line # (Acc.)**" box in Fig. 15 (see Fig. 17 for column line index) for which the floor accelerations are to be determined. To analyze multiple column lines at once, type "WF01_01,WF02_2" (without quotation marks), for example, with commas in between the indices of the column line. Enter "All" or "all" (without quotation marks) to determine the floor acceleration of all column lines.

If "**DDI**" is chosen, enter the panel index (or indices) in the "**Panel #**" box in Fig. 15 (see Fig. 17 for panel index) for which the DDIs are to be determined. To analyze multiple panels at once, type "WF01_01,WF02_2" (without quotation marks), for example, with commas in between the indices of the column line. Enter "All" or "all" (without quotation marks) to determine the DDIs of all wall panels.



Design Parameters:

Strength Design: ☑ DCI (Demand-to-Capacity Index) ☑ Base Shear ☑ Overturning Moment

Serviceability Design: ☑ Inter-Story Drift ☑ Resultant Acceleration ☑ DDI

Select Member/Column Line/Panel:

○ Individual ● Group ○ All

Individual (Group) Member: Group1 Column Line # (Disp.): WF01_01 Column Line # (Acc.): WF01_01 Panel #: WF01_01

Neglect Wind Loads On Beams Option: ● Yes ○ No

Path to RC Folder:

Peak Calculation Option:

● Observed Peak Approach (Default)
○ Multiple Points-in-Time Approach
○ Estimated Peak Approach

Discarded Initial Portion of Response Time Series [Points]:

No. of Multiple Points-in-Time:

ESWL (Equivalent Static Wind Load):

○ Yes ● No (Default) Save Effective Floor Wind Loads In:

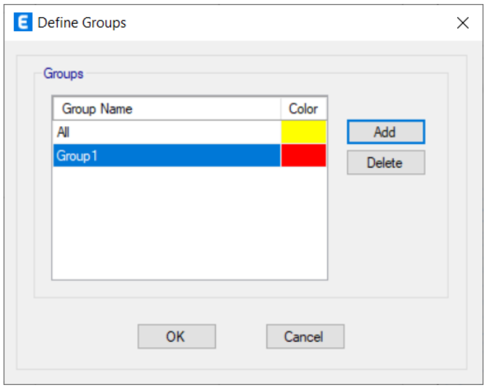
Lower Limit Requirement:

Limiting Value: ○ 80% ○ 50% ● No Limit

ASCE 7-Based Principal Loads:

Overturning Moments (X-Dir) [kN-m]: Overturning Moments (Y-Dir) [kN-m]:

Fig. 15. DAD_PBD "Design" tab and necessary inputs for constructing response surfaces.



Group Name	Color
All	🟨
Group1	🟥

Fig. 16. Example group definition window in ETABS.

The indexing of column lines and panels is detailed in Fig. 17. It follows the *"WFXX_YY"* format, where *"XX"* denotes the two-digit wall-face-number, and *"YY"* indicates the column or panel number with the index number increasing counter-clockwise. For example, the index for the column line at the top right corner (i.e., columns joining Wall Faces 2 and 3) is denoted as *"WF03_01"*. Note that each corner marks the start of a column line. For example, the index of the top left corner is *"WF04_01"*, not *"WF03_07"*. Refer to Fig. 17 for other examples.

Wall Face 1 is defined as the bottom face (wall with the lowest *y* coordinates), and Wall Face 2 is the outermost face on the right side (wall with the highest x coordinates), with the numbering also increasing counter-clockwise. Note that the center of the building is not required to be in the origin (*x* = 0, *y* = 0). It is also important for the user to eliminate any unnecessary joints that may have been included when building the basic ETABS model. This step is crucial to prevent potential misclassification of column lines and panel numbers.

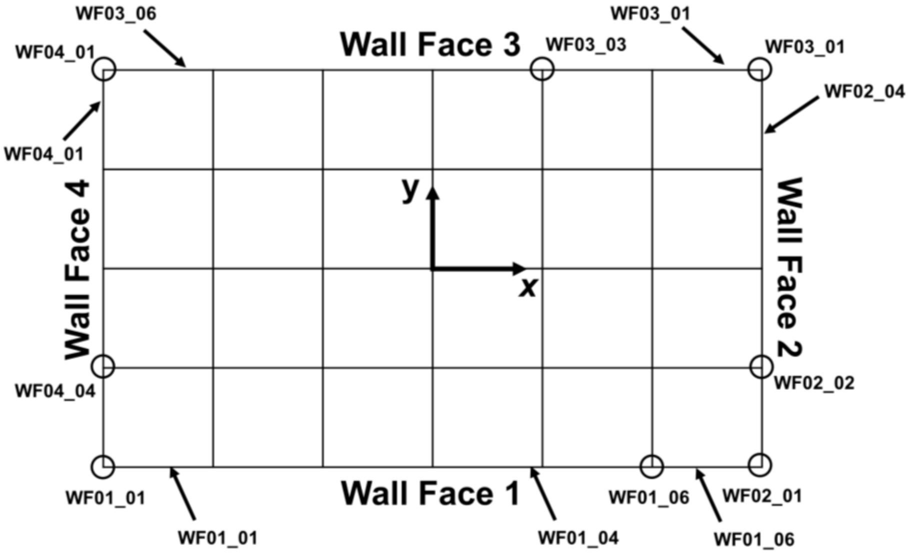


Fig. 17. Column line and panel number indexing.

Once the design parameters are set, the user can initiate the data extraction of the ETABS analysis results by clicking the "**Extract ETABS Analysis Results**" button. This action prompts the

ETABS software to process the analysis results and generate the structural responses (e.g., joint displacements, accelerations, internal forces). Note that the data extraction can be time-consuming. For reference, extracting ETABS results for 27 elements across 7 wind speeds and 36 wind directions with 7504 time-history timesteps required approximately 38 hours on a single desktop PC with eight cores and 64GB RAM. To speed up the ETABS analysis and data extraction, DAD_PBD has implemented a parallel run of ETABS using multiple computers, which is discussed in Section 2.8.

The Equivalent Static Wind load (ESWL) option [25] is currently unavailable and will be included in future versions of DAD_PBD. The details on the "**Peak Calculation Option**", "**Lower Limit Requirements**", and "**ASCE 7-Based Principal Loads**" can be found in Sections 2.6.5. and 2.6.6.

In the "**Discarded Initial Portion of Response Time Series [Points]**" box, the user should enter a positive integer number to specify the number of initial data points to be excluded from the time histories of the structural responses (e.g., internal forces, displacements, accelerations). To include all time histories, enter zero. It is recommended to discard the initial analysis data from the time-history structural response is recommended to avoid the transient response effects caused by the abrupt thrust of wind blowing into the building at rest during the structural dynamic analysis.

Once the data extraction from ETABS is complete and all the inputs are correctly entered, the user can click the "**Compute Response Surfaces**" button to construct the response surfaces for the selected design parameters. An example of a response surface for DCI_{PM} of a column member is shown in Fig. 18. After all the response surfaces are calculated, an HDF5 file named "*ResponseSurfaces.hdf5*" is saved in the "Output" folder, containing the data for response surfaces of the design parameters for the selected structural members, column lines, and panels.

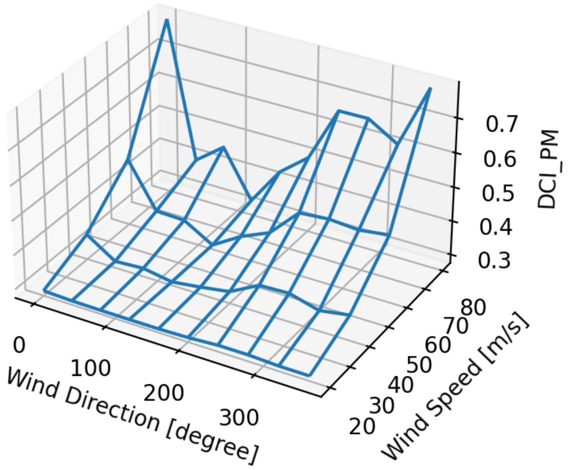


Fig. 18. Example of a response surface for DCI_{PM}.

2.6.1. Demand-to-Capacity Index (DCI)

Demand-to-Capacity Index (DCI) is an indicator of structural member adequacy, incorporating a combination of Demand-to-Capacity Ratios (DCRs) for multiple load interactions (e.g., Eqs. 18a and 18b). The DAD_PBD evaluates the performance of the member under the peak combined effect of lateral (e.g., wind) and gravity loads using the DCI. The time-history DCIs for the critical sections of wind-resisting structural members are calculated from the design strengths of the member and the time-history internal forces (e.g., axial, torsion, bending moment, and shear) from the ETABS time history dynamic analysis, at those critical sections. The peak values out of these DCI time-histories are estimated using the methods outlined in Section 2.6.5, and a response surface is created for each critical section of the member.

2.6.1.1. Steel Framed Building

For steel-framed buildings, the frame members consist of columns, braces, and beams. The DCI time-histories are calculated at the critical sections of structural members, such as both ends of columns and braces and the two ends and mid-span for beams.

Note that the current version of DAD_PBD uses in-house Python code to determine the capacity (design strength) of steel members. The Python code is developed based on the AISC manual [26] but is applicable only to Wide-flange (W-) and Hollow Structural Sections (HSS-) steel sections. Future updates may include commercial software that facilitates the calculation of design strengths for a broader range of steel member types.

The DCI equation of steel frame members simultaneously subjected to flexural and axial forces (DCI_{PM}) is based on the interaction equations from the AISC steel standard (see Eqs. (H1-1a) and (H1-1b) in ANSI/AISC 360-22 [26]):

$$If \ \frac{P_r(t)}{\phi_p P_n} \geq 0.2, \quad DCI_{PM}(t) = \frac{P_r(t)}{\phi_p P_n} + \frac{8}{9}\left(\frac{M_{rx}(t)}{\phi_m M_{nx}} + \frac{M_{ry}(t)}{\phi_m M_{ny}}\right) \tag{18a}$$

$$If \ \frac{P_r(t)}{\phi_p P_n} < 0.2, \quad DCI_{PM}(t) = \frac{P_r(t)}{2\phi_p P_n} + \left(\frac{M_{rx}(t)}{\phi_m M_{nx}} + \frac{M_{ry}(t)}{\phi_m M_{ny}}\right) \tag{18b}$$

where $P_r(t)$ is the internal axial force (positive for tensile or negative for compressive) of the member; P_n is the axial design strength (tensile or compressive according to the internal force); M_r and M_n denote the internal flexural moment and flexural design strengths of the member, respectively; the x and y subscripts denote the major and minor axis of the member, respectively; ϕ_p and ϕ_m are strength reduction factors for axial and flexural strengths of the member, respectively.

Due to the discontinuity in Eqs. (18a) and (18b), a sudden and significant increase in DCI is observed for members of $P_r(t)$ exceeding 20 % of $\phi_p P_n$, particularly when the moment contribution is relatively minor. Figure 19 provides an example of a brace exhibiting an abrupt increase in DCI_{PM} (Eqs. 18a and 18b). Figure 19(a) presents the time history of the internal axial force of the brace member subjected to wind loads scaled to a wind speed of 60 m/s. Figure 19(b) shows the corresponding DCI_{PM} calculated using Eqs. (18a and 18b). The solid green line and dashed orange line in Fig. 19(a) indicate 20 % of the tensile and compressive strengths of the brace, respectively. When the $P_r(t)$ exceeds 20 % of the tensile strength, the DCI at that moment nearly doubles compared to the DCIs at adjacent times, despite only a minor increase in the axial force.

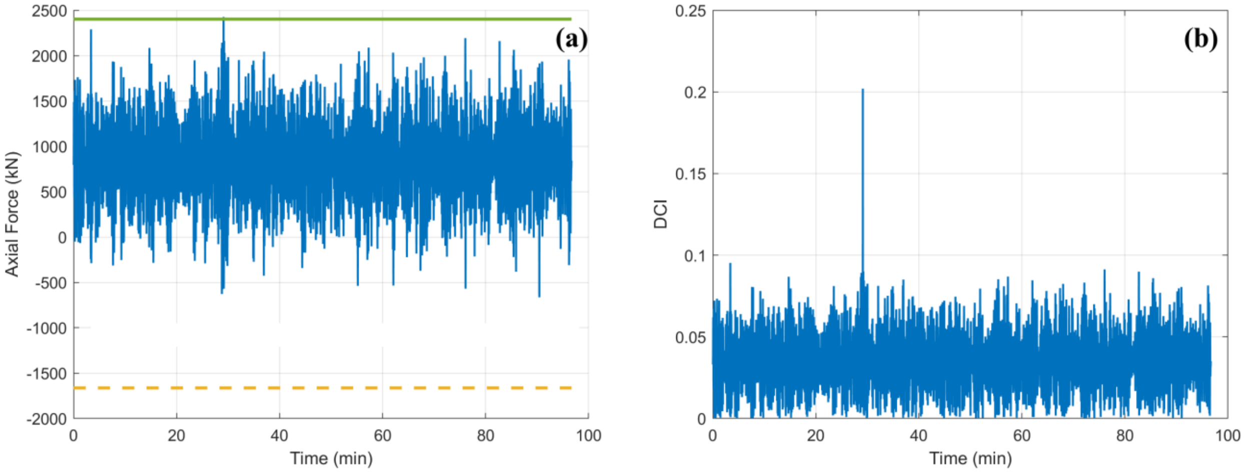


Fig. 19. Illustration of a large increase in DCI with time history of (a) axial force and (b) DCI.

To address this problem, a new method for calculating DCI without discontinuity is proposed, which adopts the ratio between the distance to demand and the failure envelope, similar to the DCI calculation of RC members in Section 2.6.1.2. Figure 20 shows the schematic drawing of the proposed method with the failure envelope (solid line) and the demand point (circle). The failure envelope is established with Eqs. (18a) and (18b) at DCI equal to unity. Distance A represents the distance from the origin to the demand point ($M_u/\phi M_n$, $P_u/\phi P_n$), indicating the demand on the member. Distance B is the distance from the origin to the failure envelope that passes through the demand point (dashed line), representing the capacity of the member. The newly introduced DCI_{PM} is defined as the ratio A/B. As shown in Fig. 20, the contour plot shows a continuous gradation in the DCI values across the ($M_u/\phi M_n$, $P_u/\phi P_n$) domain.

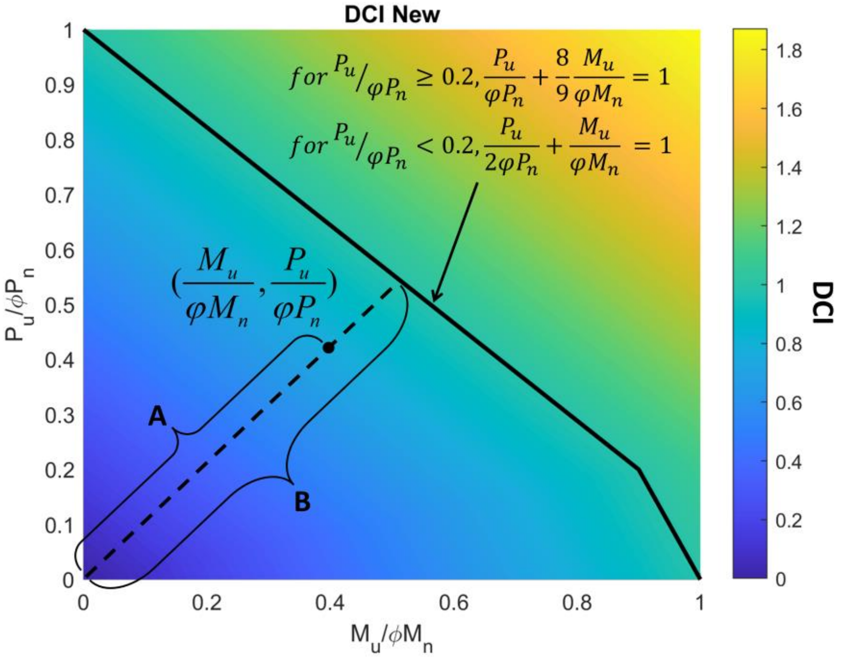


Fig. 20. Schematic drawing of the proposed *DCI_{PM}* method.

For steel frame members under shear forces only, the DCI time-history for shear (DCI_{VT}) is computed according to Eq. (19) for each principal axis. The peak DCI is then identified as the greater of the two global maxima in the principal axes.

$$DCI_{VT}(t) = \max\left(\frac{V_{rx}(t)}{\phi_v V_{nx}}, \frac{V_{ry}(t)}{\phi_v V_{ny}}\right) \tag{19}$$

where V represents the shear force; the subscripts r and n represent the internal force and the design strength of the member, respectively; and the ϕ_v represents the reduction factor for shear strength.

For a HSS-section, the DCI_{PM} and DCI_{VT} can be integrated into a single expression, as shown in Eq. (20) (see Eq. H3-6 in [26]). However, if the internal torsional force is less than or equal to 20 % of the torsional design capacity, the torsional effect is ignored.

$$If\ \frac{T_r(t)}{\phi_t T_n} > 0.2,\ DCI_{PMVT} = \left(\frac{P_r(t)}{\phi_p P_n} + \frac{M_{rx}(t)}{\phi_m P_{nx}} + \frac{M_{ry}(t)}{\phi_m M_{ny}}\right) + \left(\max\left(\frac{V_{rx}(t)}{\phi_v P_{nx}}, \frac{V_{ry}(t)}{\phi_v V_{ny}}\right) + \frac{P_r(t)}{\phi_p P_n}\right)^2 \tag{20}$$

where T represents the torsional force, and ϕ_t represents the reduction factor for torsional strength.

For beams that the wind effect is considered negligible (see Section 2.6), they are subjected only to the static gravity loads, and thus, the DCIs of the beams become no longer a function of time.

If any of the DCI values (e.g., DCI_{PM} , DCI_{VT} , DCI_{PMVT}) exceeds the required threshold (typically unity), the design of the member is considered inadequate and recommended for resizing during the re-design process.

2.6.1.2. Reinforce Concrete Buildings

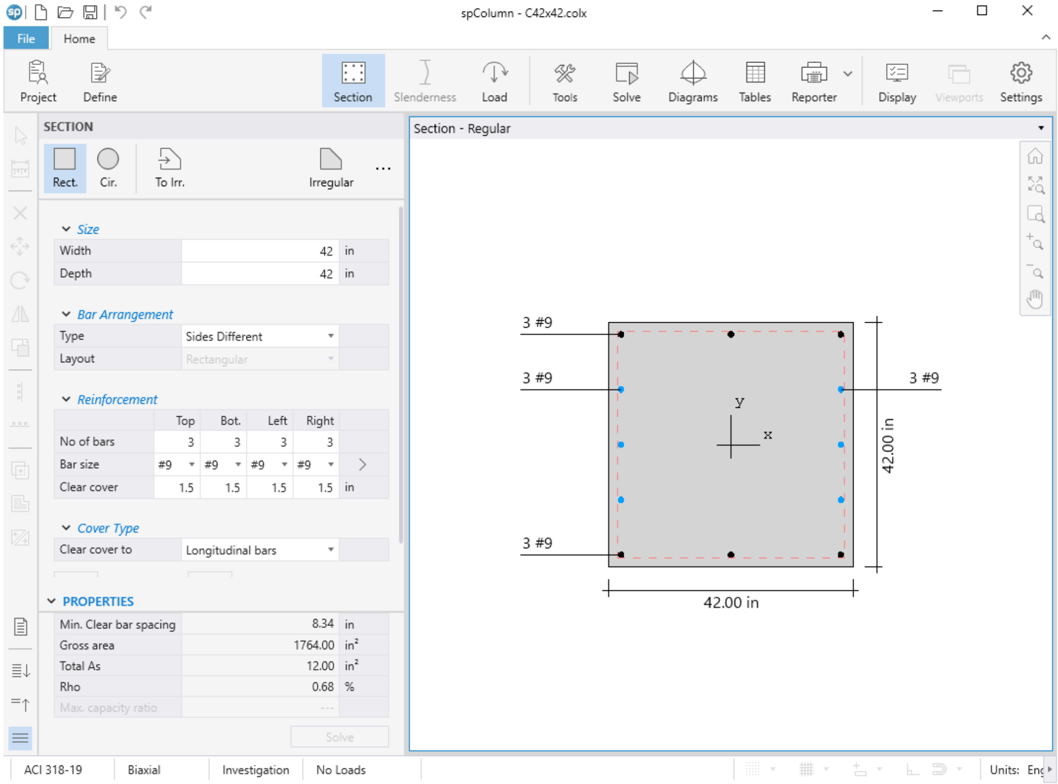
The RC members currently available in DAD_PBD for reinforced concrete building are RC columns, shear walls, and link beams. The DCI time-histories are determined at the ends of the member (i.e., two critical sections). To calculate the DCI time-history of RC members subjected to simultaneous flexural moments and axial force (DCI_{PM}), the DAD_PBD utilizes commercial design software to calculate the axial and moment capacity of the RC members from their PMM diagrams. The DAD_PBD incorporates SpColumn from StructurePoint [23], a tool widely used among structural engineers, for calculating member strengths. Provided that the PMM input file format is consistent, the engineers may use any PMM calculation program of their choice. Details of the format are specified in Appendix D.

Through the SpColumn user interface, the user can freely manipulate the section and rebar sizes and obtain the biaxial bending and axial force interaction strength surface (i.e., PMM interaction) of the RC members. Figure 21 shows an example of a PMM interaction diagram of a rectangular-shaped RC column in SpColumn, where P is the axial force, and M is the combined bending moments about the x and y axes. Note that the x and y axes defined in this section are the local axes defined in SpColumn, not the global axes defined in ETABS. SpColumn defines positive axial load as compression and negative axial load as tension. In SpColumn, the section is rotated in 10-degree increments from 0 degrees to 360 degrees, and the M_x and M_y moment capacities are computed, creating an M_x-M_y contour for each level of axial load. In other words, the bending moments are only available for a neutral axis angle between 0 and 360 degrees with 10-degree increments where the neutral axis angle (η) is defined as:

$$\eta = \tan^{-1}\left(M_y / M_x\right) \tag{21}$$

By applying this process across the full range of axial loads, a three-dimensional failure surface is constructed. As shown in Fig. 21(b), SpColumn provides both the nominal (red dashed-dotted line) and factored failure surface (blue dashed line) to support enhanced understanding of the section capacity. The factored failure surface (or PMM interaction) can be exported into a CSV file, which will be used to determine the DCI_{PM} of the RC members. The user can choose the metric (kN and m) or the US customary unit (kip and ft) system in SpColumn and must ensure that the unit complies with the unit system selected in Section 2.4.1 when exporting the CSV file. Note that the CSV file of the factored failure surface exported from SpColumn excludes the 80 % cut-off of the axial loads (blue solid line). Once the three-dimensional PMM surface is obtained and the CSV files are uploaded to the DAD_PBD, a 2D cubic interpolation with a 1-degree increment of neutral axis angle and the 80 % cut-off of the axial strength are performed within Python to increase the resolution and comply with ACI 318.

To calculate the time-history DCI for a member, the neutral axis angle η is determined at each timestep using the $M_{rx}(t)$, $M_{ry}(t)$. The corresponding DCI at each timestep is obtained from the sliced 2-D PM surface associated with η at that time. Figure 22 shows an example of a sliced 2D PM surface (solid line) and the demand point (Point D) where $\overline{OD}$ is the distance from the origin to the demand point ($M_r(t)$, $P_r(t)$), and $\overline{OC}$ is the distance from the origin to the failure envelope that passes through the demand point (dashed line), representing the capacity. The $DCI_{PM}(t)$ of the RC member is defined as $\overline{OD}/\overline{OC}$. The same process is used to determine the PMM interaction of shear walls and link beams. For more details on the operation of SpColumn, refer to the SpColumn v10.10 manual [23].



SECTION

Size

Width	42	in
Depth	42	in

Bar Arrangement

Type	Sides Different
Layout	Rectangular

Reinforcement

	Top	Bot.	Left	Right	
No of bars	3	3	3	3	
Bar size	#9	#9	#9	#9	
Clear cover	1.5	1.5	1.5	1.5	in

Cover Type

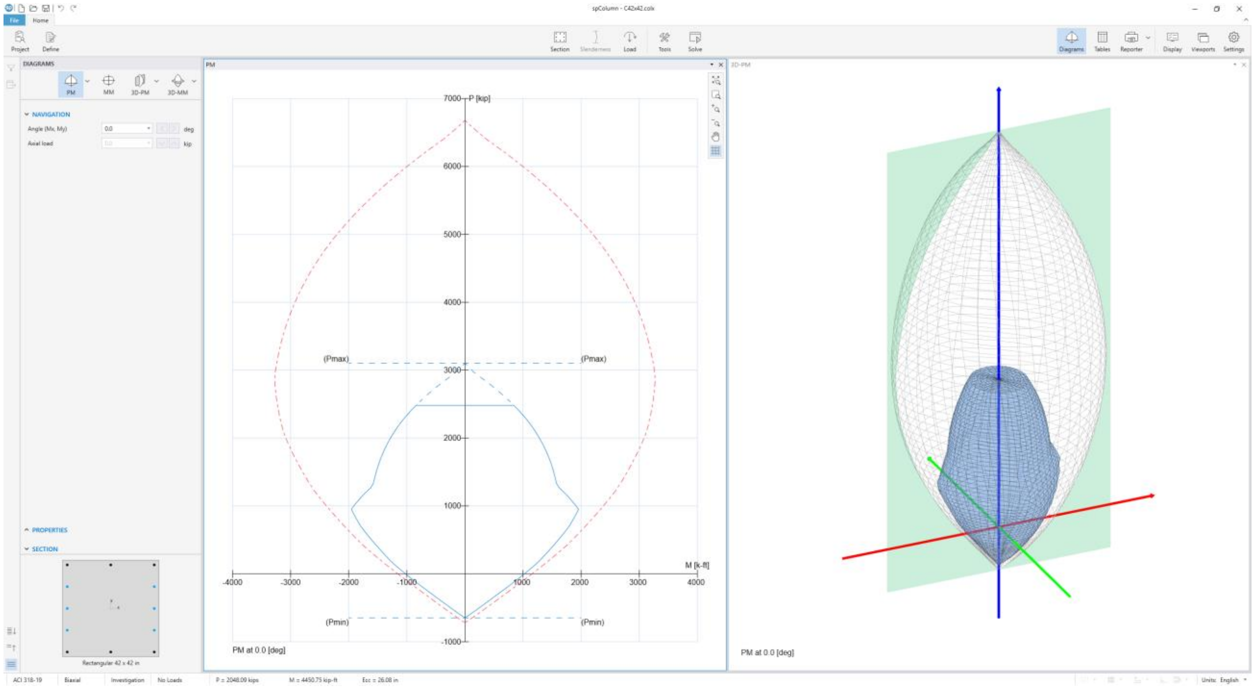
Clear cover to	Longitudinal bars

PROPERTIES

Min. Clear bar spacing	8.34	in
Gross area	1764.00	in^2
Total As	12.00	in^2
Rho	0.68	%
Max. capacity ratio	---	

ACI 318-19 | Biaxial | Investigation | No Loads | Units: Eng

(a) Column section view in SpColumn



NAVIGATION

Angle (Mx, My)	0.0	deg
Axial load	0.0	kip

ACI 318-19 | Biaxial | Investigation | No Loads | P = 2048.09 kips | M = 4450.75 kip-ft | Ecc = 26.08 in | Units: English

(b) Two dimensional PM failure surfaces at 0 degrees (left) and three dimensional PMM failure surfaces (right) in SpColumn

Fig. 21. An example of a PMM interaction diagram of a rectangular-shaped RC column in SpColumn.

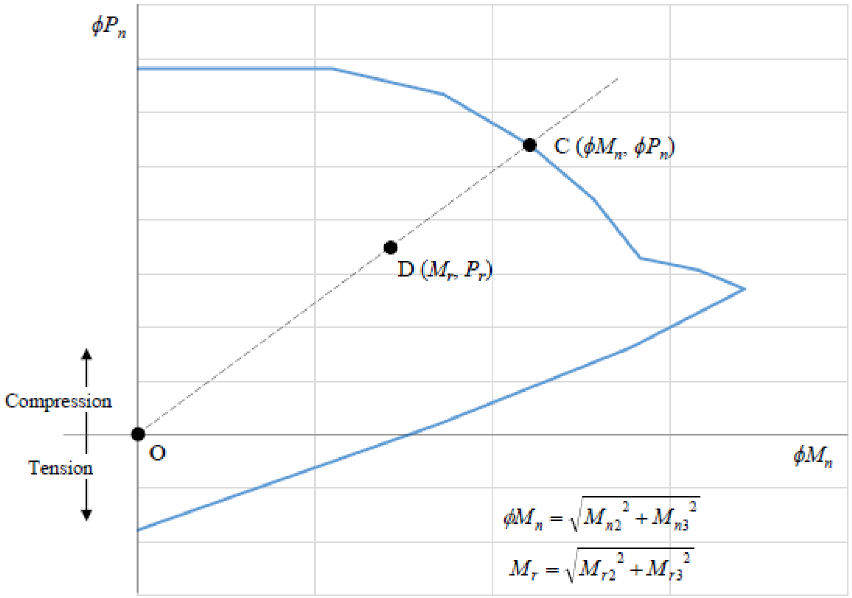


Fig. 22. Illustration of 2D PM surface and demand point of a RC member.

Similar to the beams for steel frame buildings, when the wind effect on link beams can be assumed negligible (see Section 2.6), the DCI becomes no longer a function of time.

For RC members under shear forces and torsion, the DCI time-history for shear and torsion (*DCI*$_{VT}$) is calculated using Eq. (22):

$$DCI_{VT}(t) = \frac{\sqrt{V_{ux}(t)^2 + V_{uy}(t)^2 + \left(\frac{T_u(t)\,p_h b_w d}{1.7{A_{oh}}^2}\right)^2}}{\phi_v(V_c + V_s)} \tag{22}$$

where V denotes the shear force; the subscripts ux and uy denote the internal force in the x- and y-axis, respectively, and subscripts c and s denote the design strength of the concrete and rebar of the member, respectively; T_u denotes the internal torsional force; p_h denotes the perimeter enclosed by the centerline of the outermost closed stirrups; b_w denotes the width of the member; d denotes the distance from extreme compression fiber to the centroid of longitudinal tension reinforcement; A_{oh} denotes the area enclosed by the centerline of the outermost closed stirrups; and the ϕ_v denotes the reduction factor for shear strength. It is advised to refer to ACI 318-14 [27] for the precise definition of b_w and d as the definition may differ for various RC members.

The current version of DAD_PBD employs an in-house Python code, based on the ACI 318-14 [27], to determine the design shear and torsional strengths for rectangular-shaped members according to their RC schedule. Future updates may incorporate commercial software, enabling strength calculations for a wider variety of shapes.

If any DCI values (e.g., DCI_{PM}, DCI_{VT}) exceed the required limit (typically unity), the design of the member is considered inadequate and recommended for resizing during the re-design process.

To upload the RC schedule to the DAD_PBD, click the "**Browse**" button to locate the folder that contains the Excel files for the RC schedules, as shown in Fig. 15. The file directory of the folder will appear in the "**Path to RC folder**" once the folder is located. Note that the Excel files must be named "Column_Schedule.xlsx" for the column schedule, "ShearWall_Schedule" for the shear wall schedule, and "LinkBeam_Schedule" for the link beam, and should contain the names of the element, the compressive strength of the concrete (f'_c) and yield strength of the steel (f_{ys}), the dimension of the element, the rebar information, and the directory path to PMM CSV files. Refer to Appendix E for the details on the Excel files for the schedule for each member and Fig. 23 shows an example of the RC folder containing the Excel files of the RC member schedules.

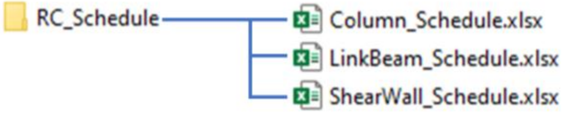


Fig. 23. Example of the RC Folder containing the Excel files of the RC member schedules.

2.6.2. Inter-story Drift Ratio

The equations for the time-histories of the inter-story drift ratio for each floor at a column line in the x- and y-axis directions, $d_{n,X}(t)$ and $d_{n,Y}(t)$, are expressed in Eqs. (23) and (24), respectively:

$$d_{n,X}(t) = \frac{\left|X_n(t) - X_{n-1}(t)\right|}{h_n} \tag{23}$$

$$d_{n,Y}(t) = \frac{\left|Y_n(t) - Y_{n-1}(t)\right|}{h_n} \tag{24}$$

where $X(t)$ and $Y(t)$ denote the absolute displacements from ETABS analysis along the x-axis and y-axis (global), respectively; the subscript n denotes the floor on the n^{th} floor; and h_n denotes the story height between the n^{th} and n-1st floors.

2.6.3. Resultant Floor Acceleration

The equation for the time history of the magnitude of the resultant floor acceleration for each floor at a column line, $|a_n|(t)$, is expressed in Eq. (25):

$$\left|a_n\right|(t) = \sqrt{\ddot{X}_n^2(t) + \ddot{Y}_n^2(t)} \tag{25}$$

where $\ddot{X}_n(t)$ and $\ddot{X}_n(t)$ denote the accelerations from ETABS analysis along the x- and y-axis (global) on the n^{th} floor, respectively.

2.6.4. Deformation Damage Index (DDI)

The Deformation Damage Index (DDI) is another serviceability design parameter based on elastic displacement. For buildings where significant or atypical displacements are expected, DDI can be used to evaluate the potential damage inflicted by shear strain on the architectural components of the building [6]. Adopted from the ATC Design Guide 3 [28], the design level acceptance criteria (i.e., DDI limit) for serviceability design for various architectural components, such as exterior cladding, interior partitions, and elevators, are provided in Table 1. The DDI equation is expressed as the following in the Prestandard [6]:

$$DDI_n(t) = 0.5\left|\frac{x_{n,A}(t) - x_{n,C}(t)}{h_n} + \frac{x_{n,B}(t) - x_{n,D}(t)}{h_n} + \frac{y_{n,D}(t) - y_{n,C}(t)}{l_n} + \frac{y_{n,B}(t) - y_{n,A}(t)}{l_n}\right| \quad (26)$$

where I_n denotes the length of the panel on the n^{th} floor, and the subscripts A, B, C, and D denote the location of the panel joints, as shown in Fig. 24. It is important to note that $x_n(t)$ and $y_n(t)$ are the local x and y coordinates of the desired panel, not the global coordinates (e.g., $X_n(t)$ and $Y_n(t)$ in Eqs. (23) and (24)). For example, the $x_n(t)$ and $y_n(t)$ shall be $Y_n(t)$ and $X_n(t)$ for panels that are aligned on the walls in the y-direction (e.g., WF2 and WF4 in Fig. 17).

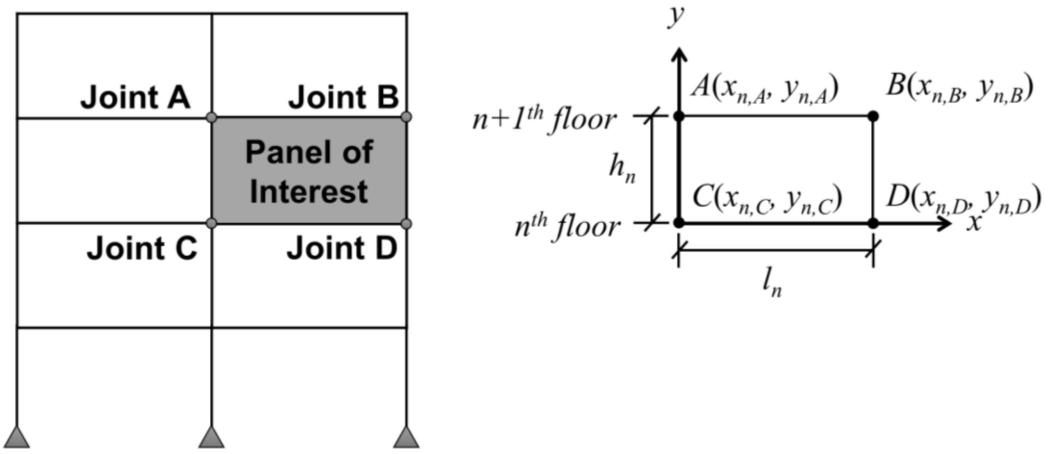


Fig. 24. Terminology for computation of Deformation Damage Index (DDI).

Table 1. Recommended DDI limits for serviceability design from ATC Design Guide 3 [28].

Architectural Component		DDI Limit
Exterior Cladding	Brick veneer on metal studs	0.0025[1]
	Brick veneer on unreinforced masonry	0.0025[1,2]
	Plaster or stucco	0.0025[3]
	Architectural precast	0.0025[4]
	Stone clad precast	0.0025[4]
	Architectural metal panel	0.0100[5]
	Curtain wall, window wall	0.0025[6]
Interior Partitions	Gypsum drywall, plaster	0.0025[7]
	Concrete unreinforced masonry	0.0015[8]
	Tile, hollow clay brick	0.0005[9]
Elevators	Drywall enclosure	0.0025[10]

[1] Steel relief angles supporting the brick are provided at each floor with 3/8 in. soft joints and 3/8 in. control joints are provided in the brick at each column bay.
[2] Control joints are provided in masonry walls and/or isolation joints (3/8 in. soft joints) are provided between CMU and structural frame.
[3] Panelized wall with 3/8 in. control joints used at each floor line and between each column bay.
[4] Assumes flexible and deformation-controlled connections of panels to floors or columns with ¾ in. joints between panels. Panel connections to floors or frames are simply supported or determinant.
[5] Metal panels are designed with this limit or as defined by manufacturer. Other building elements generally demand stricter limits.
[6] Applicable to most off-the-shelf systems. The manufacturer shall be consulted, and the limit defined in specifications. American Architectural Manufacturers Association (AAMA) wall testing recommended for most projects unless similar test results exist.
[7] Soft joints recommended between floors as defined in ASTM C754 to allow for LL deflection and racking.
[8] Applies if CMU is constructed hard against floors and structural frame. Soft joints recommended between floors between structural frame to accommodate building sway and to eliminate stiffness contribution to lateral load resisting system.
[9] Assumes wall system constructed hard against floors and structural frame. Soft joints recommended between floors and to structural frame to accommodate building sway.
[10] Proper performance of elevator system requires a knowledge of building mode shapes, frequencies, deflections, and accelerations under design wind loads. Information shall be placed in contract documents for elevator manufacturer design.

2.6.5. Peak Estimation Option

For the peak estimation, the DAD_PBD offers two options: 1) the “**Observed Peak Approach (Default)**” and 2) the “**Multiple-Points-In-Time (MPIT) Approach**”. The default option is the observed peak approach, which uses the full time-histories of the individual wind effects (e.g., $P_r(t)$, $M_{rx}(t)$, and $M_{ry}(t)$ for $DCI_{PM}(t)$) to determine the peak value of the time-history combined wind effects. Alternatively, the MPIT approach calculates the peak value of the combined wind effect only at the times of the highest n peaks from the time-histories of the individual wind effects with the benefit of a significantly reduced computational time. If the user chooses the MPIT approach option, the n points must be entered in the “**No. of Multiple Points-in-Time**” box in Fig. 15. The MPIT approach is recommended for at least 30 points. For a detailed explanation of the methodology and significance of the MPIT approach, refer to [29].

2.6.6. Lower Limit Requirement

In Section 31.4.4. of the ASCE 7-22 [2], the Main Wind Force Resisting System (MWFRS) loads from wind tunnel testing should be:

"… limited such that the overall principal loads in the *x* and *y* directions are not less than 80 % of those that would be obtained from Chapter 27 … The overall principal load for buildings shall be based on the overturning moment for flexible buildings and the base shear for other buildings. … The limiting values of 80 % may be reduced to 50 % for the MWFRS … if either of the following conditions applies:

> 1. There were no specific influential buildings or objects within the detailed proximity model.
>
> 2. Loads and pressures from supplemental tests for all significant wind directions in which specific influential buildings or objects are replaced by the roughness representative of the adjacent roughness condition, but not rougher than Exposure B, are included in the test results."

In accordance with ASCE 7-22 provision above, the DAD_PBD software offers the user an option to apply an adjustment factor (γ) to the DCI value for cases where the overturning moment (M_o) estimated by the DAD procedure is less than 80 % or 50 % of the M_o estimated from the ASCE 7-based wind loads (Chapter 27 of the ASCE 7):

$$\gamma = \frac{0.8 \text{ or } 0.5}{M_o^{DAD} / M_o^{ASCE7}} \tag{27}$$

where the superscripts DAD and $ASCE7$ denote the estimation methods based on DAD and ASCE 7, respectively. The numerator shall be 0.5 if one of the above two conditions is satisfied.

If the adjustment factor is applied, the user must select the **Limiting Value** (i.e., 80 % or 50 %) and provide the overturning moments estimated from the ASCE 7-based wind loads in the "**Overturning Moments (X-Dir)**" and "**Overturning Moments (Y-Dir)**" text boxes as shown in Fig. 15. Generally, the ASCE 7-based overturning moments are already calculated from ETABS using the "ASCE 7 Wind Load" during the preliminary design process. Note that if the DCI box is unchecked, the **Limiting Value**, **Overturning Moments (X-Dir)**, and **Overturning Moments (Y-Dir)** text boxes are disabled. To ignore the ASCE lower limit requirement, click the "**No Limit**" button.

2.7. MRI Design Curve

The final step of the DAD procedure is constructing MRI design curves as a function of MRI for the selected design parameters, using the wind climatological data and the response surfaces (Section 2.6). Wind directionality is a crucial factor in structural design for wind as the climatologically most unfavorable wind directions in a building site typically do not coincide with the aerodynamically or dynamically most critical directions for the building [19]. Determining the wind effects on the local site is a crucial component of the DAD procedure. This step ensures an accurate assessment of the wind directionality effects.

With the MRI design curves, the design parameters associated with the specified MRI can be determined by assessing their respective design curves at the given MRI.

The climatological data must include peak directional wind speeds with long MRIs. Since the MRI for climatological data is generally recommended to be at least three times greater than the MRI used in the building design, these datasets are often generated numerically through measurements or simulations [30]. Publicly available wind climatological data can be obtained from Sections 1 and 5 of www.nist.gov/wind, or site-specific data should be obtained from the wind engineer. Refer to Appendix B for the required format of the wind climatological data compatible with the software.

The steps outlined below describe the procedure for constructing the MRI design curve for a given design parameter using the climatological data and the response surface:

1. The design parameter values (e.g., DCI, inter-story drift, floor acceleration, DDI) for particular wind speeds and directions of each storm are obtained by mapping the storm's directional wind speeds onto the response surface of the design parameter.
2. The peak design value within each storm is determined.
3. The peak design values for all storms are ranked in order, and their MRIs are calculated using nonparametric statistics as shown in Eq. (28). The k^{th} highest ranking MRI ($\overline{N}_k$) is expressed as:

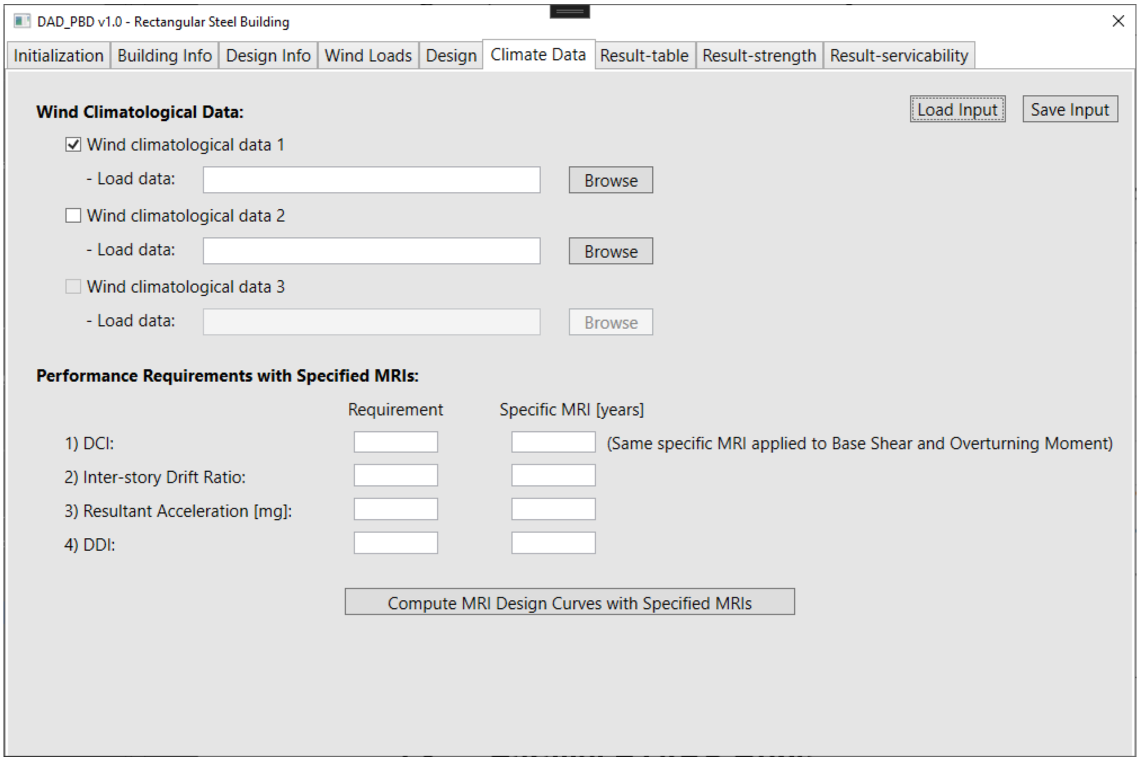
$$\overline{N}_k = \left[1 - \exp\left(-\frac{\lambda k}{n_{storm} + 1}\right)\right]^{-1} \tag{28}$$

where λ is the mean annual rate of storm arrival, and n_{storm} is the total number of storms in the climatological data.

Under the **"Climate Data"** tab (Fig. 25), the user must upload the building site-specific wind climatological data. The current version of DAD_PBD supports two types of wind climatological data. For instance, hurricane data can be used for wind climatological data 1 and synoptic wind data for wind climatological data 2. To consider mixed climate (i.e., both hurricane and synoptic winds), the user must select both checkboxes with climate data uploaded. Climatological data 3 is currently unavailable as it is reserved for another storm type, for example, non-synoptic winds such as thunderstorms, for a future edition. By incorporating multiple storm types, DAD_PBD can evaluate the design wind effects across different wind climates. For more details on the methodology, refer to [25, 31].

The user is also required to specify both the performance requirement value (i.e., acceptance criteria) and its corresponding MRI for each design parameter under the "**Performance Requirements with Specific MRIs**" panel in Fig. 25. These specific MRIs are based on their performance objectives (e.g., refer to [6]). Note that the same specific MRI for DCI is applied to that of base shear and overturning moment. With all inputs entered, the user can generate the MRI design curves by clicking the "**Compute MRI Design Curves with Specific MRIs**" button.

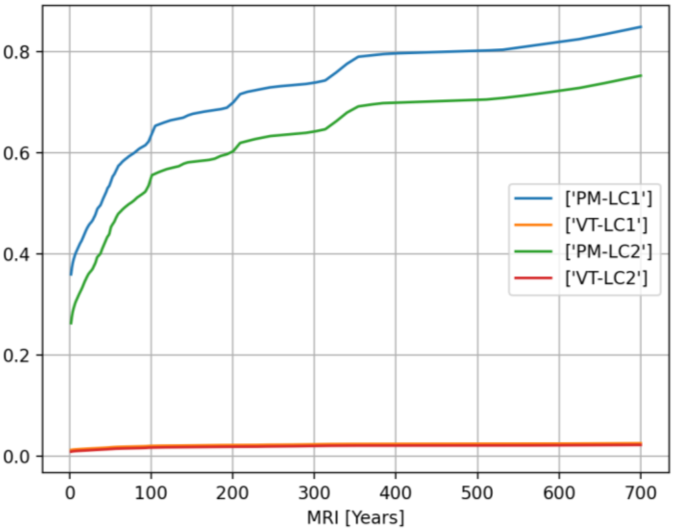
Figure 26 shows examples of MRI design curves for (a) DCI_{PM} and DCI_{VT} and for (b) inter-story drift ratios, respectively. For serviceability design (i.e., inter-story drift, acceleration, and DDI), the peak design value profile along the height of the building can also be displayed (see Fig. 46). Note that DCI, Inter-story Drift Ratio, and DDI are dimensionless quantities, whereas acceleration is measured in milli-g (g/1000), where g denotes the gravitational acceleration (= 9.81 m/s^2).



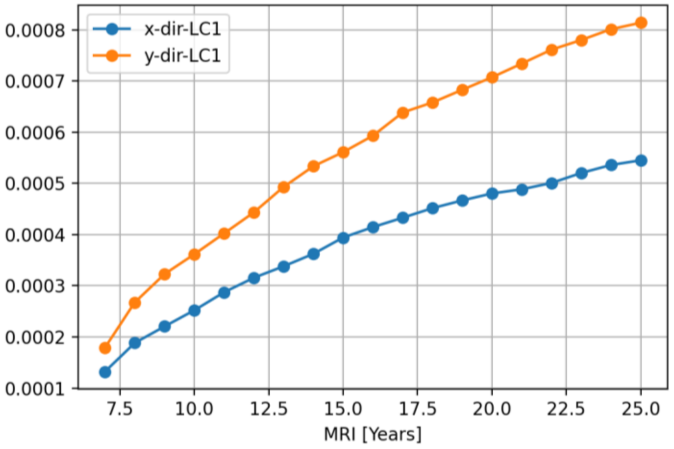
☑ Wind climatological data 1
☐ Wind climatological data 2
☐ Wind climatological data 3

(Same specific MRI applied to Base Shear and Overturning Moment)

Fig. 25. DAD_PBD "Climate Data" tab for inputs for MRI design curve.



(a) MRI design curves for *DCI$_{PM}$* and *DCI$_{VT}$*



(b) MRI design curves for inter-story drift ratio

Fig. 26. Examples of MRI design curves for (a) *DCI$_{PM}$* and *DCI$_{VT}$* and for (b) inter-story drift ratio.

2.8. Parallel ETABS Runs

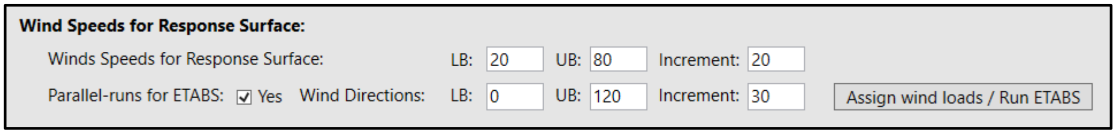
One major concern regarding the DAD_ETABS software, the predecessor of DAD_PBD, reported in NIST Technical Note 2236 was the excessively long computational time of the ETABS wind analyses and data extraction [12].

In DAD_PBD, multiple ETABS analyses and data extraction can be executed concurrently on multiple computers in parallel mode, provided there is a sufficient available number of ETABS licenses. This parallel ETABS run feature can significantly reduce computational time, approximately proportional to the number of computers utilized. For example, the 38 hours of data extraction time, approximated in Section 2.6, would decrease to 9.5 hours with four parallel ETABS runs, assuming identical computer processing power.

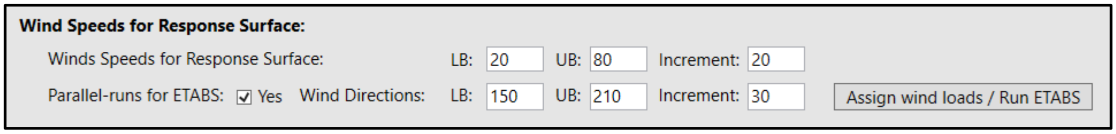
The main computer designated for all analyses, including the wind load calculation and the MRI design curve, is referred to as the primary computer. All the other computers used for parallel analysis and data extraction in ETABS are termed secondary computers. To carry out the simultaneous parallel ETABS runs on multiple computers, the user must download and execute the DAD_PBD.exe file and install the necessary software and packages listed in Section 2.2 on all secondary computers, except for the Matplotlib package. The steps to execute the parallel ETABS runs are as follows:

1. Before starting the parallel ETABS runs, the user must calculate the floor wind loads with the “**Parallel-runs for ETABS**” checkbox selected in Fig. 8. This will generate multiple hdf5 files, instead of one (*“forces.hdf5”*), named *“forces_XXX.hdf5”* where *“XXX”* denotes the three-digit wind directions. The CSV files for the floor loads are generated the same as shown in Fig. 14. On the secondary computer(s), type in the wind directions the user desires to analyze in the “**Wind Directions**” text box for “**Parallel-runs for ETABS**” (see Fig. 8). Figure 27 shows an example of the input data for three computers if the user decides to proceed with the DAD procedure, covering wind direction 0 to 360 degrees with 30 degree increments with ETABS runs evenly distributed among the three computers. Note that the primary computer can also be used for the parallel-ETABS runs. The input for Fig. 27 will perform ETABS analyses for wind direction 0, 30, 60, and 90 degrees on the first computer (Fig. 27(a)); wind directions 120, 150, 180, and 210 degrees on the second computer (Fig. 27(b)); and wind directions 240, 270, 300, and 330 degrees on the third computer (Fig. 27 (c)). Note that the wind direction 360 degrees is the same as 0 degrees and will not be analyzed, but make sure to include wind direction 360 degrees as mentioned in Section 2.5. If 360 degrees is not included, the software will not analyze the last wind direction. Additionally, the parallel ETABS runs feature does not require an even distribution, as shown in Fig. 27. Depending on each computer's memory and processing power, the user may want to allocate more (or less) wind direction ETABS runs to optimize the computational time. As shown in Fig. 27, the user must also ensure that the ranges and increments of both wind direction and wind speed for the “**Wind Speeds for Response Surface**” field are consistent across the primary and secondary computers. In other words, the input for the “**Wind Speeds for Response Surface**” field should all be the same for all three computers. The wind directions under the “**Pressure Data From Wind Tunnel Test / CWE Data**” panel should comprise all the wind directions selected in all the secondary computers. Furthermore, the user must copy all the files and folders that are located inside the “**Save Outputs In**” folder (e.g., ETABS model and the “Output” folder) to the secondary computers. If the directory path is different from the primary computer, make sure that the directory paths (e.g., path to ETABS model, Path to API DDL file, Save Outputs In) are modified accordingly so that the software can access the correct folders and files on the secondary computer(s). To avoid copying files and folders, the user may use the cloud drive to save and share the files. However, it has been noticed that running the ETABS files on cloud storage reduces the computational speed significantly. Once the files and folder have been properly copied over to the secondary computer (s), click the “**Assign wind loads / Run ETABS**” button on each computer. Once the ETABS analyses are finished, each computer will generate a folder of all the ETABS models with assigned wind direction under the “*ETABS_Model*” folder. Within the *“ETABS_Model”* folder, a subfolder

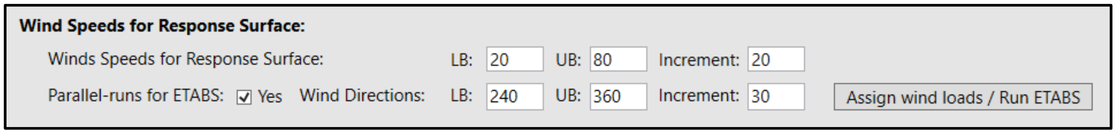
named in the format *“Model_XXX”* is generated folder, containing all ETABS files associated with that direction. The *“XXX”* represents the three-digit wind direction.


Wind Speeds for Response Surface:
Winds Speeds for Response Surface: LB: 20 UB: 80 Increment: 20
Parallel-runs for ETABS: ☑ Yes Wind Directions: LB: 0 UB: 120 Increment: 30

(a) Input for the first computer


Wind Speeds for Response Surface:
Winds Speeds for Response Surface: LB: 20 UB: 80 Increment: 20
Parallel-runs for ETABS: ☑ Yes Wind Directions: LB: 150 UB: 210 Increment: 30

(b) Input for the second computer


Wind Speeds for Response Surface:
Winds Speeds for Response Surface: LB: 20 UB: 80 Increment: 20
Parallel-runs for ETABS: ☑ Yes Wind Directions: LB: 240 UB: 360 Increment: 30

(c) Input for the third computer

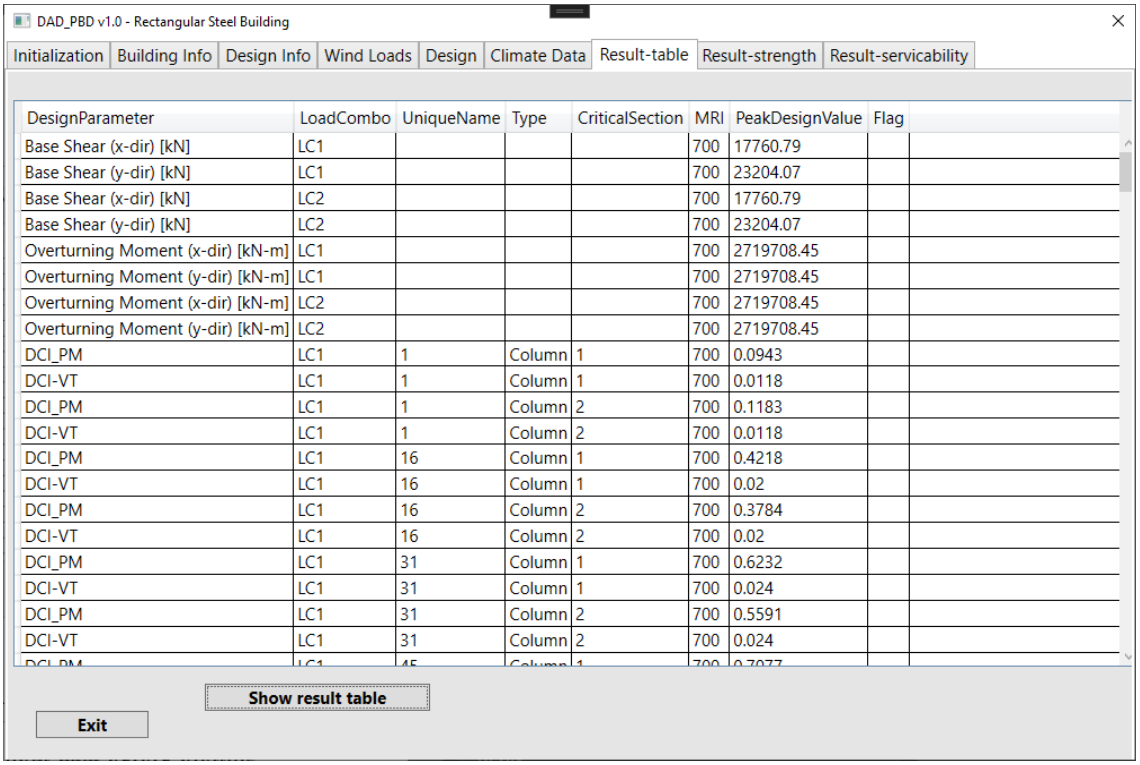
Fig. 27. Examples of wind direction input for multi-runs for ETABS for three computers.

2. Under the “**Design**” tab, select the desired design parameters according to Section 2.6. Then, the user may proceed to the data extraction by clicking the “**Extract ETABS Analysis Results**” button on all computers. After the data extraction is complete, the hdf5 files containing ETABS results will be generated in the *“Output”* folder of each computer. The hdf5 files are named *“ETABS_results_XXX.hdf5”*, where the *“XXX”* denotes the three-digit wind direction.
3. Under the “**Design**” tab, enter necessary inputs (e.g., Peak Calculation Option (Section 2.6.5), Lower Limit Requirement (Section 2.6.6), ASCE7-Based Principal Loads (Section 2.6.6) and click the “**Compute Response Surfaces**” button on all computer(s) to proceed with computing response surfaces. Once the response surface construction is finished, a hdf5 file will be generated in the “Output” folder for each computer. The hdf5 files are named *“ResponseSurface_XXX_YYY.hdf5”*, where the *“XXX”* and *“YYY”* denote the three-digit of the first and the last wind direction, respectively. For example, the computers with the inputs in Fig. 27 will produce hdf5 files named *“ResponseSurfaces_000_120.hdf5”* (Fig. 27(a)), *“ResponseSurfaces_150_210.hdf5”* (Fig. 27(b)), and *“ResponseSurfaces_240_330.hdf5”* (Fig. 27(c)).
4. Copy all the response surface hdf5 files from the secondary computer(s) to the primary computer and click the “**Merge RS hdf5 files**” button on the primary computer in Fig. 15. An hdf5 file named *“ResponseSurfaces.hdf5”* will be generated with all the response surface files merged.
5. Carry out the MRI design curve analysis on the primary computer (refer to Section 2.7). The user must ensure that the *“Selected_Members_Info.hdf5”* file is copied to the “Output” folder if the primary computer is not used for the previous steps.

Note that the ETABS folders (e.g., *"Model_XXX"* folder) and the extracted data files (e.g., *"ETABS_results_XXX.hdf5"*) are saved in sequence after the completion of each wind direction. In case of any unexcepted interruption, the user may check the *"ETABS_Model"* or *"Output"* folder to see in which wind direction the interruption had happened and may restart the remaining process. This allows breaks between ETABS analyses or data extractions.

2.9. Results

Three tabs are available for the user to view the DAD_PBD results. Under the "**Result-table**" tab (Fig. 28), a summary of all results is tabulated for the selected design parameters. Any frame member or joint whose design parameters exceed their design requirements specified in Section 2.7 is marked with an "X" in the "flag" column, indicating that a re-design is recommended. The user is advised to re-design the necessary members in the ETABS building model and repeat Steps 4 through 7 from Section 2.1 with the updated ETABS model. For re-design steps, the base ETABS model will be the updated ETABS model, and thus, the "**Path to ETABS Model**" should also be updated to match the directory path of the revised ETABS model before initiating the analysis in Step 4.



DesignParameter	LoadCombo	UniqueName	Type	CriticalSection	MRI	PeakDesignValue	Flag
Base Shear (x-dir) [kN]	LC1				700	17760.79	
Base Shear (y-dir) [kN]	LC1				700	23204.07	
Base Shear (x-dir) [kN]	LC2				700	17760.79	
Base Shear (y-dir) [kN]	LC2				700	23204.07	
Overturning Moment (x-dir) [kN-m]	LC1				700	2719708.45	
Overturning Moment (y-dir) [kN-m]	LC1				700	2719708.45	
Overturning Moment (x-dir) [kN-m]	LC2				700	2719708.45	
Overturning Moment (y-dir) [kN-m]	LC2				700	2719708.45	
DCI_PM	LC1	1	Column	1	700	0.0943	
DCI-VT	LC1	1	Column	1	700	0.0118	
DCI_PM	LC1	1	Column	2	700	0.1183	
DCI-VT	LC1	1	Column	2	700	0.0118	
DCI_PM	LC1	16	Column	1	700	0.4218	
DCI-VT	LC1	16	Column	1	700	0.02	
DCI_PM	LC1	16	Column	2	700	0.3784	
DCI-VT	LC1	16	Column	2	700	0.02	
DCI_PM	LC1	31	Column	1	700	0.6232	
DCI-VT	LC1	31	Column	1	700	0.024	
DCI_PM	LC1	31	Column	2	700	0.5591	
DCI-VT	LC1	31	Column	2	700	0.024	

Fig. 28. Example result summary table.

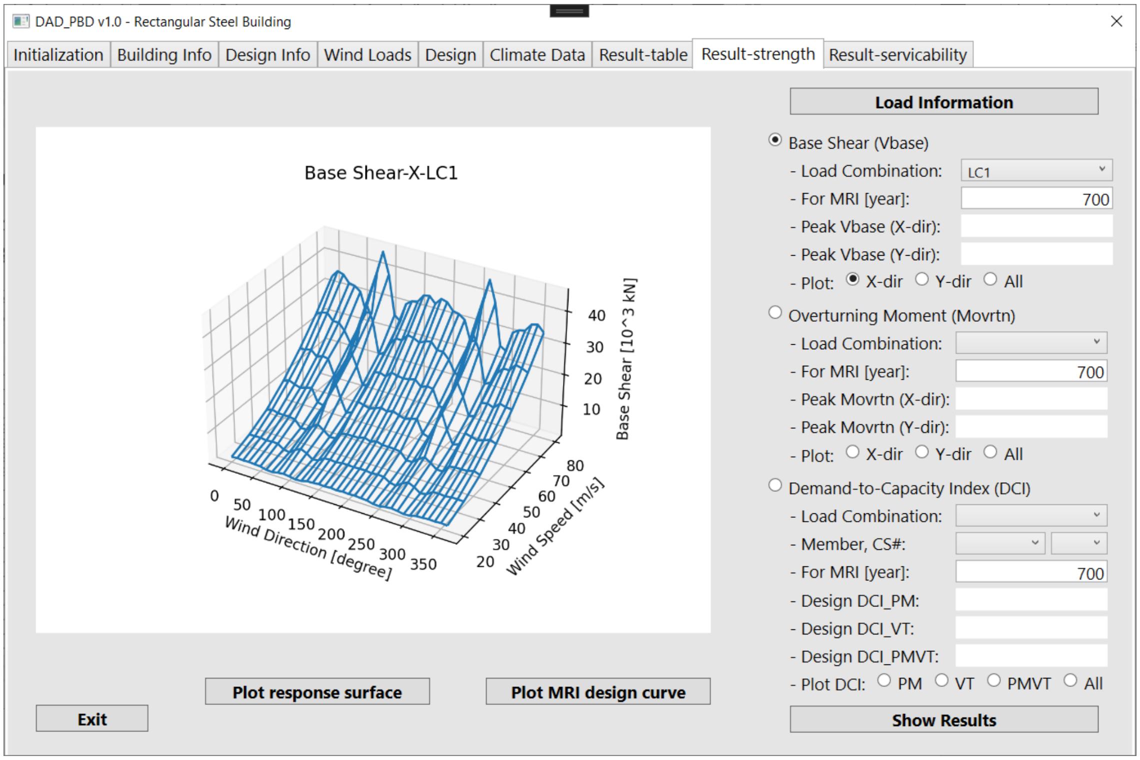
Under the "**Result-strength**" tab (Fig. 29) and "**Result-serviceability**" tab (Fig. 30), the analysis plots and results can be displayed for strength and serviceability design parameters, respectively. It is important to note that the "**Load Information**" button at the top of each result tab must be clicked to load the input data and populate the dropdown menus before plotting any figures or displaying results.

To view the peak design results in numbers, select the desired design parameter (i.e., Base shear, DCI, acceleration, DDI) and load combination. Additionally, select the desired member and critical section number ("CS#") for DCI, and the floor level and column line (panel index for DDI) for serviceability design. Clicking the "**Show results**" button will display the peak design values in the text box. If "max" is chosen in the load combination, the maximum value across all load combinations will be displayed. Note that the specific MRI value in the "**For MRI**" box can be modified if the user wishes to identify the design value at a different MRI. However, the MRI must be an integer and less than the value specified in the "**Climate Data**" tab as the result data is only available up to the specified MRI. To view design parameter values for higher MRI, the user must re-run the MRI design curve analysis in the "**Climate Data**" tab.

To view the result plots, select the desired design parameter and load combination. Additionally, select the desired member and critical section number ("CS#") for DCI, and the floor level and column line (panel index for DDI) for serviceability design. Then, click either the "**Plot response surface**" button or the "**Plot MRI design curve**" button to generate the respective plots. Any figures displayed on the screen will be saved and can be accessed in the "*Display*" folder. Figures 29 and 30 display examples of the response surface plot for base shear (x-dir) and the MRI design curve of the 45th-floor acceleration, respectively.

When viewing results and generating figures, there are several notes to be taken:

1. For DCI, there are two critical sections defined for columns and braces, and three for beams as described in Sections 2.6.1.1 and 2.6.1.2. Thus, if the user chooses 3 for "**CS#**" for columns, braces, shear walls, or link beams, a warning message will appear.
2. For all design parameters under strength design and inter-story drift ratio, if the user selects the "**All**" radio button under "**Plot**" and clicks the "**Plot MRI Design Curve**" button, the MRI design curves for both x- and y-directions (or all DCIs for DCI) and for all load combinations will be displayed. However, this option is only applicable to MRI design curve figures. Clicking the "**Plot Response Surface**" button with the "**All**" button active will trigger a warning message.
3. For all design parameters under serviceability design, if the user selects "**All**" for the floor level and clicks the "**Plot MRI Design Curve**" button, a vertical profile of the design parameters, showing values at all floor levels, will be displayed.

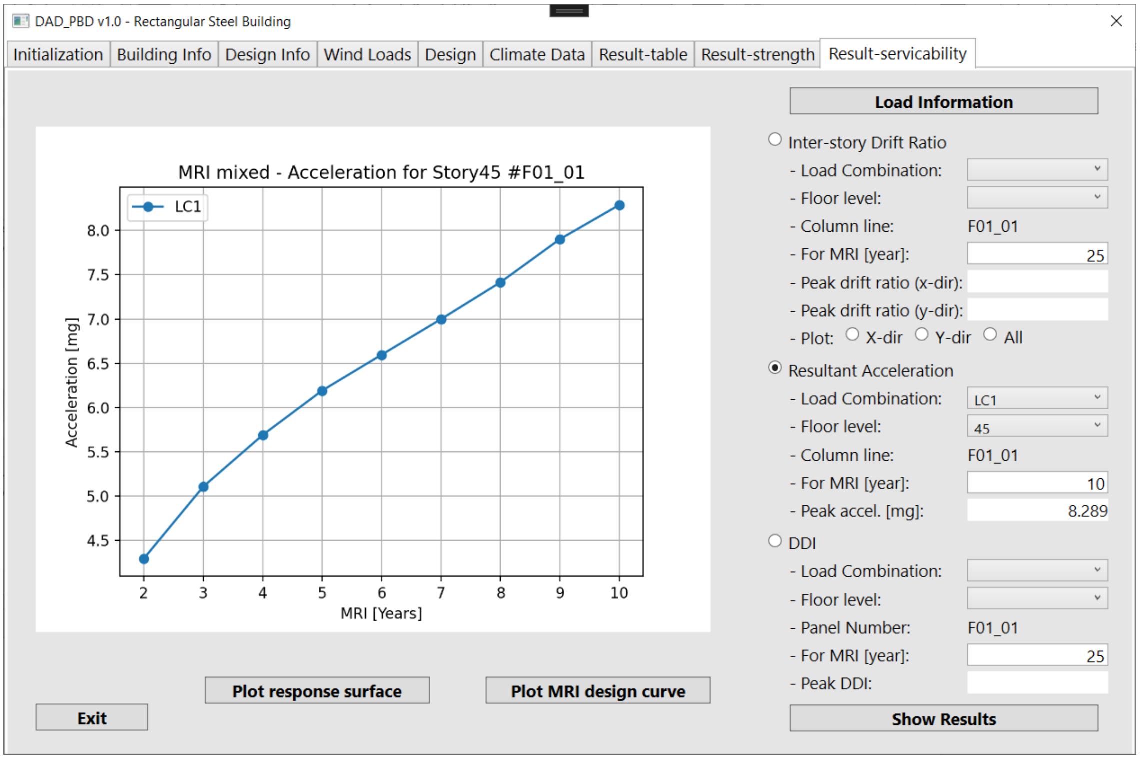


● Base Shear (Vbase)
- Load Combination: LC1
- For MRI [year]: 700
- Peak Vbase (X-dir):
- Peak Vbase (Y-dir):
- Plot: ● X-dir ○ Y-dir ○ All

○ Overturning Moment (Movrtn)
- Load Combination:
- For MRI [year]: 700
- Peak Movrtn (X-dir):
- Peak Movrtn (Y-dir):
- Plot: ○ X-dir ○ Y-dir ○ All

○ Demand-to-Capacity Index (DCI)
- Load Combination:
- Member, CS#:
- For MRI [year]: 700
- Design DCI_PM:
- Design DCI_VT:
- Design DCI_PMVT:
- Plot DCI: ○ PM ○ VT ○ PMVT ○ All

Fig. 29. Example of "Result-strength" tab with Base Shear (*x*-dir) response surface plot.



○ Inter-story Drift Ratio
- Load Combination:
- Floor level:
- Column line: F01_01
- For MRI [year]: 25
- Peak drift ratio (x-dir):
- Peak drift ratio (y-dir):
- Plot: ○ X-dir ○ Y-dir ○ All

● Resultant Acceleration
- Load Combination: LC1
- Floor level: 45
- Column line: F01_01
- For MRI [year]: 10
- Peak accel. [mg]: 8.289

○ DDI
- Load Combination:
- Floor level:
- Panel Number: F01_01
- For MRI [year]: 25
- Peak DDI:

Fig. 30. Example of "Result-serviceability" tab with floor acceleration MRI design curve plot.

3. Reinforced Concrete Building Design Example

This Technical Note presents a design example of the Reinforced Concrete CAARC building. For the steel-frame building example, refer to the NIST Technical Note 2293 [14].

3.1. Performance Objective and Acceptance Criteria

In the design example, the performance objective is assumed to be "Occupant Comfort," where the building motions and vibrations shall minimize the occupant discomfort, and the structural system shall remain elastic [6]. To achieve this performance objective, the following acceptance criteria were established:

- Strength Design:

  DCI with a 700-year MRI for members in a linear structural system ≤ 1

- Serviceability Design:

  Acceleration with a 10-year MRI ≤ 20 mg (from Fig. 31)

  Inter-story drift ratio with a 25-year MRI ≤ 0.0025 [2]

  DDI with a 25-year MRI ≤ 0.0025 (from Table 6-1 of [28])

Note that the acceleration limit of a building is determined based on its natural frequency of vibration, as illustrated in Fig. 31. The figure shows the maximum acceptable peak accelerations of office buildings for three specified MRIs. The acceleration limit of 20 mg was provisionally established assuming that the natural frequency of the building is approximately 0.2 Hz. However, this acceptable acceleration limit should be re-evaluated after completing the dynamic modal analysis (see Section 3.7.1).

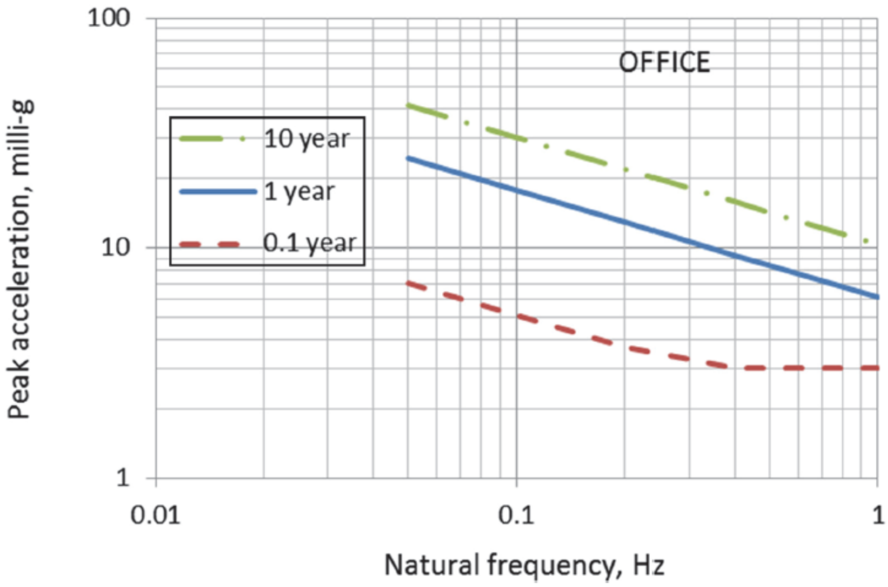


Fig. 31. Maximum acceptable peak acceleration versus natural frequency for office buildings, for 10-year, 1-year, and 0.1-year return periods (ATC Design Guide 3 Figure 4-1 [28]; used with permission).

3.2. Preliminary Design Loads

On all floors of the building, unreduced uniform live loads of 50 psf (2.39 kPa) for office use were applied with no live load reduction (see Section 2.3), superimposed dead loads of 15 psf (0.72 kPa) were used for the ceiling and mechanicals, and cladding superimposed dead loads of 0.15 kip/ft (2.19 kN/m) were applied along the edges of the building for the window system.

3.3. Load Combinations

Although the user may use different load combinations, the following two strength design load combinations and one serviceability design load combination are typically implemented in the DAD procedure [7]:

- Strength Design:

  Load Combination 1 (LC_1) = $1.2DL + 1.0LL + 1.0WL$

  Load Combination 2 (LC_2) = $0.9DL + 1.0WL$

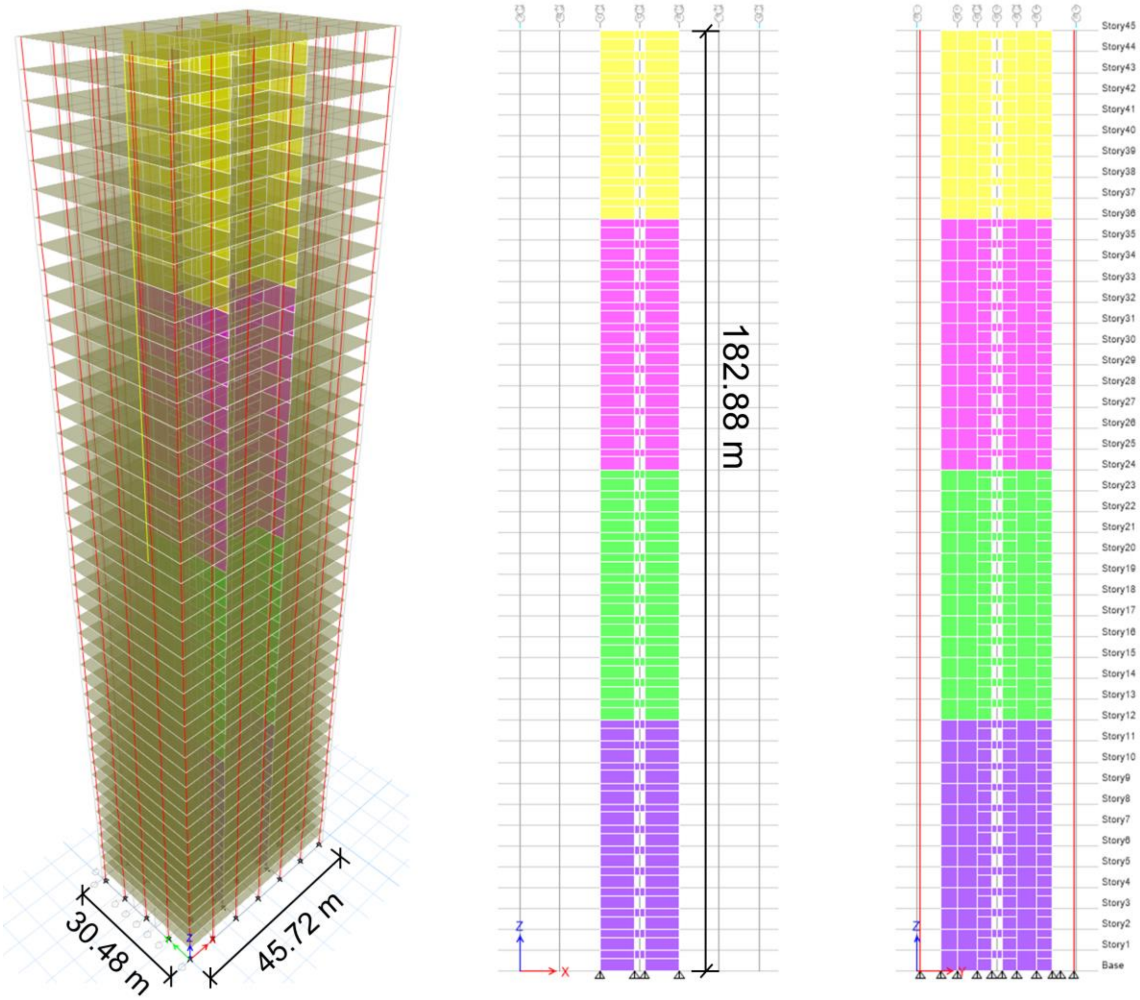
- Serviceability Design (see Eq. CC.2-3 in ASCE 7-22 [2]):

  $LC_{srv} = 1.0DL + 0.5LL + 1.0WL$

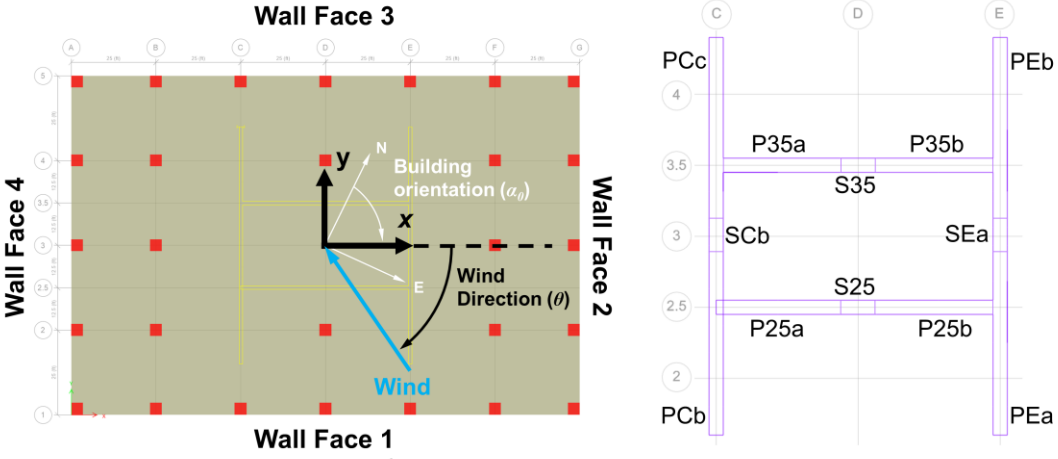
where DL, LL, and WL denote dead, live, and wind loads, respectively. The RC building design example in this report used the same load combinations.

3.4. Building Information

The RC CAARC Building was assumed to be a Risk Category II office building with an MRI of 700 years of design strength. The building is rectangular in plan with dimensions of 180 m in height, 45.72 m in width, and 30.48 m in depth, arranged in a 6 × 4 bay layout (7.62 m × 7.62 m in each bay). The floors were considered rigid diaphragms. Figure 32 shows the ETABS views of the 45-story RC CAARC building. The building has shear walls near the center, which are divided into four zones, reducing thickness, reinforcement, and concrete strength as elevation increases. Link beams connect shear walls where wall openings occur. Each level has six wall pier groups, grouped into two design groups due to symmetry. The wind direction (θ) and the Wall Face definition adhere to the same sign convention as Fig. 17.



(a) 3D view (b) Section 2.5 view (2.5) (c) Section E view



(d) Plan view of 45th floor (e) Shear wall and link beam labels

Fig. 32. ETABS views of the RC CAARC building.

3.5. Aerodynamic Pressure Coefficient and Climate Data

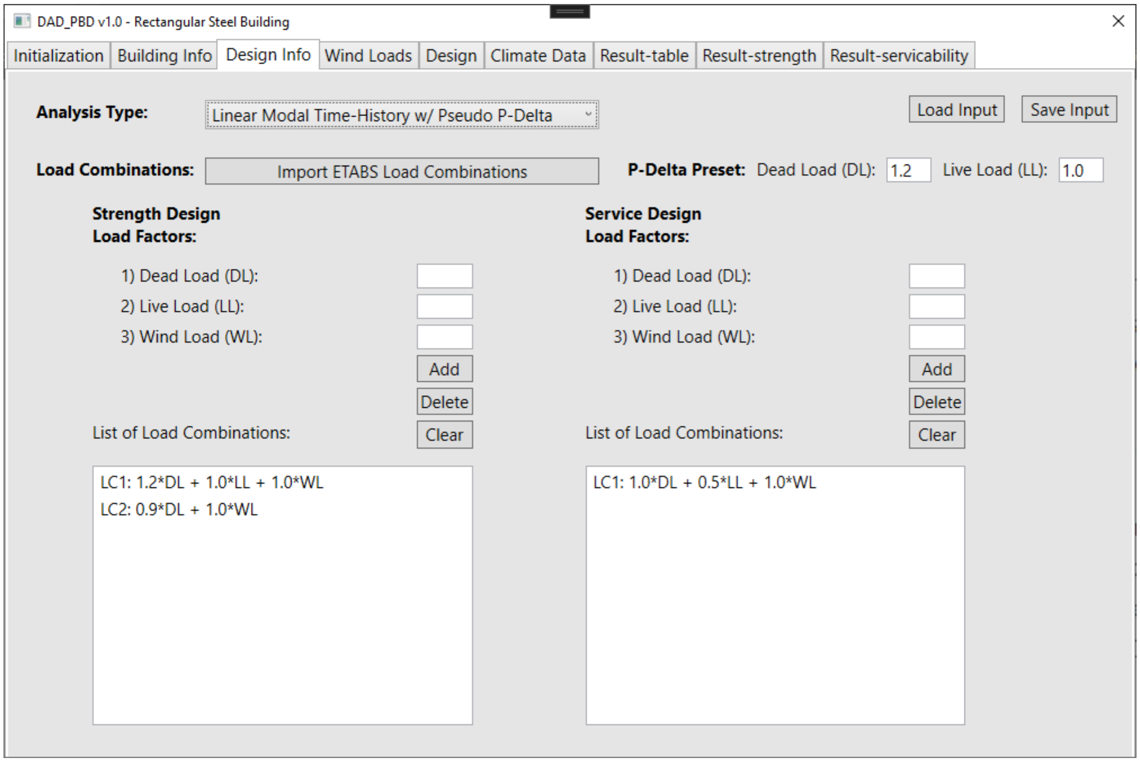
The CAARC building is assumed to be located in Newark, New Jersey with an open terrain exposure (Exposure C). The pressure coefficient data was measured in the Boundary Layer Wind Tunnel of the Prato (Italy) Inter-University Research Centre on Building Aerodynamics and Wind Engineering (CRIAC IV-DIC) under Exposure C terrain condition with a length scale of 1:500, sampling frequency of 250 Hz, 7504 data points for each pressure tap, and a reference mean wind speed at the top of the building model of 23.2 m/s [32]. The tap layouts are shown in Appendix A.1. The site-specific climatological data was obtained from [25].

3.6. Design Example Inputs and Acceptance Criteria

Table 2 provides a comprehensive summary of all the inputs used in the design example, including the wind load inputs. In this design example, shear walls, link beams, and columns located on the 1st, 16th, 25th, and 37th floor are selected for DCI, and column line “WF01_01” and panel “WF01_01” were chosen for drift/acceleration and DDI, respectively. Figures 33-36 show the windows of the “**Wind Loads**”, “**Design**”, and “**Climate Data**” tabs, respectively, with required inputs.

Table 2. Design example input summary.

Tab Name	Input Item	Input Value
Design Info	Analysis Type	Linear Modal Time History w/ Pseudo P-Delta
	Strength Design Load Factors	LC1: 1.2DL+1.0LL+1.0WL LC2: 0.9DL+1.0WL
	Serviceability Design Load Factors	LC1: 1.0DL+0.5LL+1.0WL
	P-Delta Preset	DL: 1.2
		LL: 1.0
Wind Loads	Wind Direction LB [Deg.]	0
	Wind Direction UB [Deg.]	360
	Wind Direction Increment [Deg.]	10
	Model Scale	500
	Reference Wind Speed at Rooftop [m/s]	23.2
	Sampling Rate [Hz]	250
	Interpolation Method	Cubic
	Loading Type	Concentrated at Geometric Center
	Wind Speed LB [m/s]	20
	Wind Speed UB [m/s]	70
	Wind Speed Increment [m/s]	10
Design	Peak Calculation Option	MPIT Approach
	Number of Discarded Initial Points	200
	Number of Points for MPIT	30
	Individual (Group) Member	N/A
	Column Line # (Disp.)	WF01_01
	Column Line # (Acc.)	WF01_01
	Panel #	WF01_01
	Neglect Wind Loads on Beams	No
	Limiting Value	80 %
	ASCE 7 Overturning Moments (X-Dir) [kN-m]	2022469.8917
	ASCE 7 Overturning Moments (Y-Dir) [kN-m]	1238141.7689
Climate Data	DCI Requirement	1.0
	DCI Specific MRI [years]	700
	Inter-story Drift Requirement	0.0025
	Inter-story Drift Specific MRI [years]	25
	Acceleration Requirement [mg]	25
	Acceleration Specific MRI [years]	10
	DDI Requirement	0.0025
	DDI Specific MRI [years]	25



Analysis Type: Linear Modal Time-History w/ Pseudo P-Delta

Load Combinations:

P-Delta Preset: Dead Load (DL): 1.2 Live Load (LL): 1.0

Strength Design
Load Factors:

1) Dead Load (DL):
2) Live Load (LL):
3) Wind Load (WL):

List of Load Combinations:

LC1: 1.2*DL + 1.0*LL + 1.0*WL
LC2: 0.9*DL + 1.0*WL

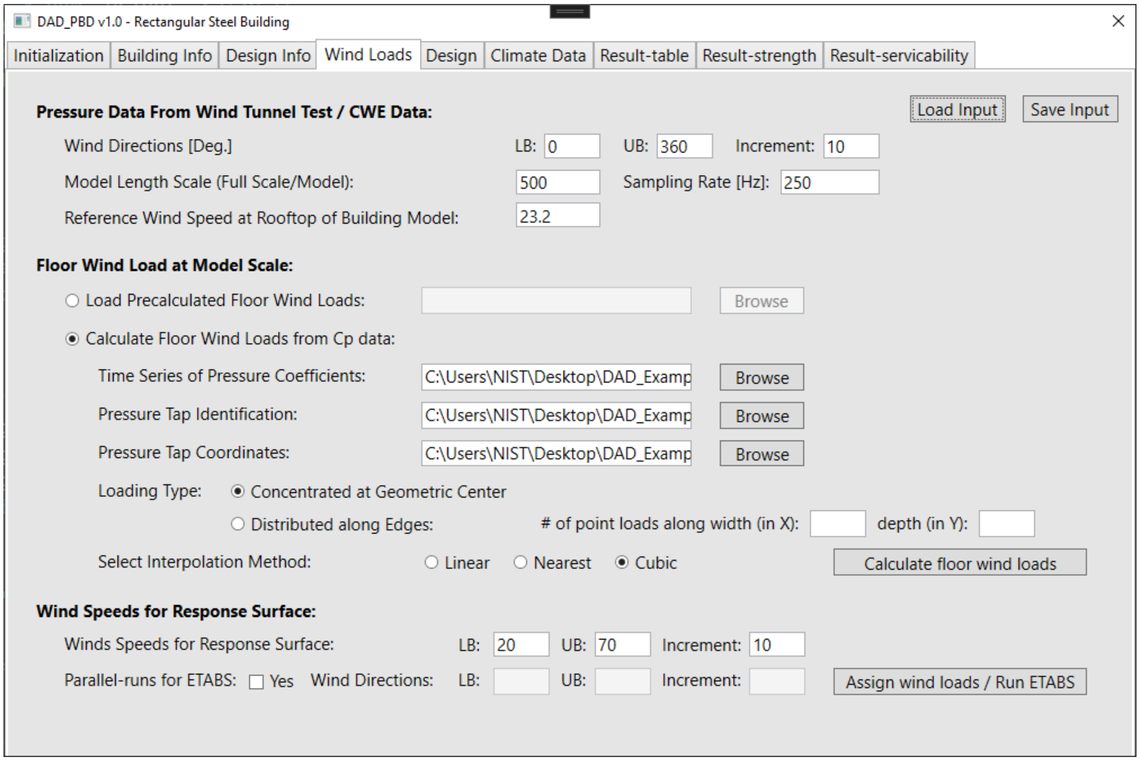
Service Design
Load Factors:

1) Dead Load (DL):
2) Live Load (LL):
3) Wind Load (WL):

List of Load Combinations:

LC1: 1.0*DL + 0.5*LL + 1.0*WL

Fig. 33. Design example inputs for “Design Info” tab.



Pressure Data From Wind Tunnel Test / CWE Data:

Wind Directions [Deg.] LB: 0 UB: 360 Increment: 10
Model Length Scale (Full Scale/Model): 500 Sampling Rate [Hz]: 250
Reference Wind Speed at Rooftop of Building Model: 23.2

Floor Wind Load at Model Scale:

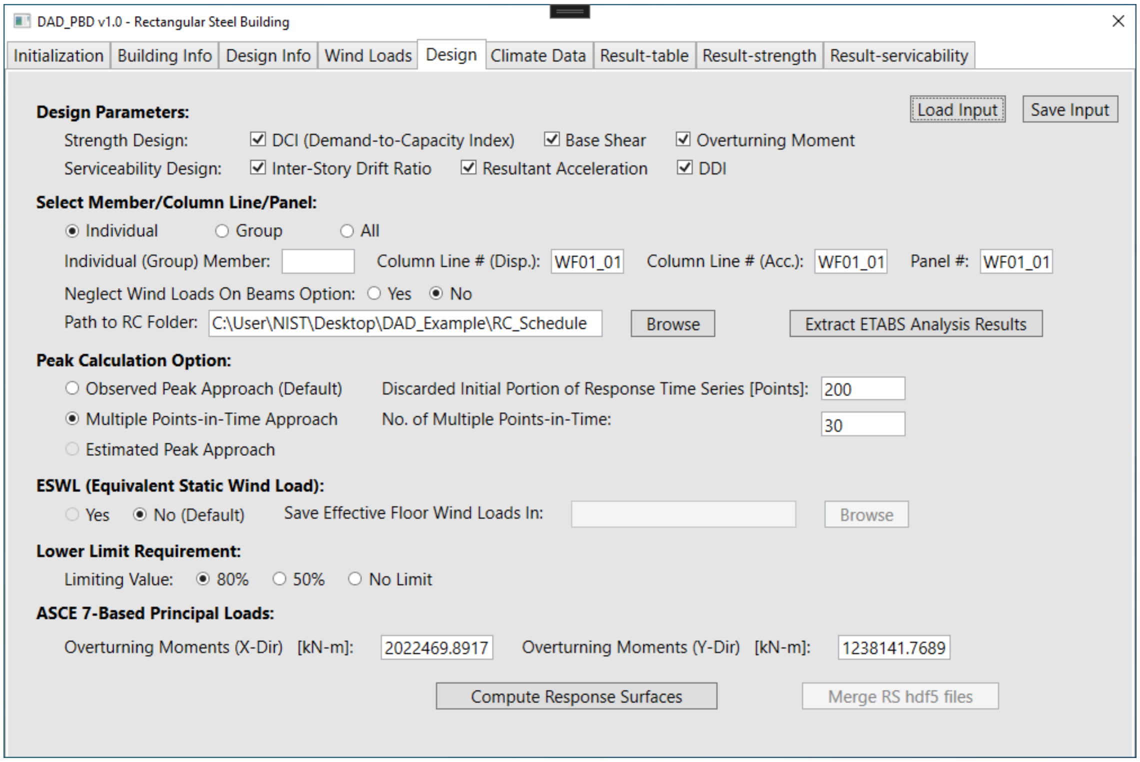
○ Load Precalculated Floor Wind Loads:
● Calculate Floor Wind Loads from Cp data:

Time Series of Pressure Coefficients: C:\Users\NIST\Desktop\DAD_Examp
Pressure Tap Identification: C:\Users\NIST\Desktop\DAD_Examp
Pressure Tap Coordinates: C:\Users\NIST\Desktop\DAD_Examp
Loading Type: ● Concentrated at Geometric Center
○ Distributed along Edges: # of point loads along width (in X): depth (in Y):
Select Interpolation Method: ○ Linear ○ Nearest ● Cubic

Wind Speeds for Response Surface:

Winds Speeds for Response Surface: LB: 20 UB: 70 Increment: 10
Parallel-runs for ETABS: ☐ Yes Wind Directions: LB: UB: Increment:

Fig. 34. Design example inputs for “Wind Loads” tab.



Design Parameters:

Strength Design: ☑ DCI (Demand-to-Capacity Index) ☑ Base Shear ☑ Overturning Moment

Serviceability Design: ☑ Inter-Story Drift Ratio ☑ Resultant Acceleration ☑ DDI

Select Member/Column Line/Panel:

● Individual ○ Group ○ All

Individual (Group) Member: Column Line # (Disp.): WF01_01 Column Line # (Acc.): WF01_01 Panel #: WF01_01

Neglect Wind Loads On Beams Option: ○ Yes ● No

Path to RC Folder: C:\User\NIST\Desktop\DAD_Example\RC_Schedule

Peak Calculation Option:

○ Observed Peak Approach (Default) Discarded Initial Portion of Response Time Series [Points]: 200

● Multiple Points-in-Time Approach No. of Multiple Points-in-Time: 30

○ Estimated Peak Approach

ESWL (Equivalent Static Wind Load):

○ Yes ● No (Default) Save Effective Floor Wind Loads In:

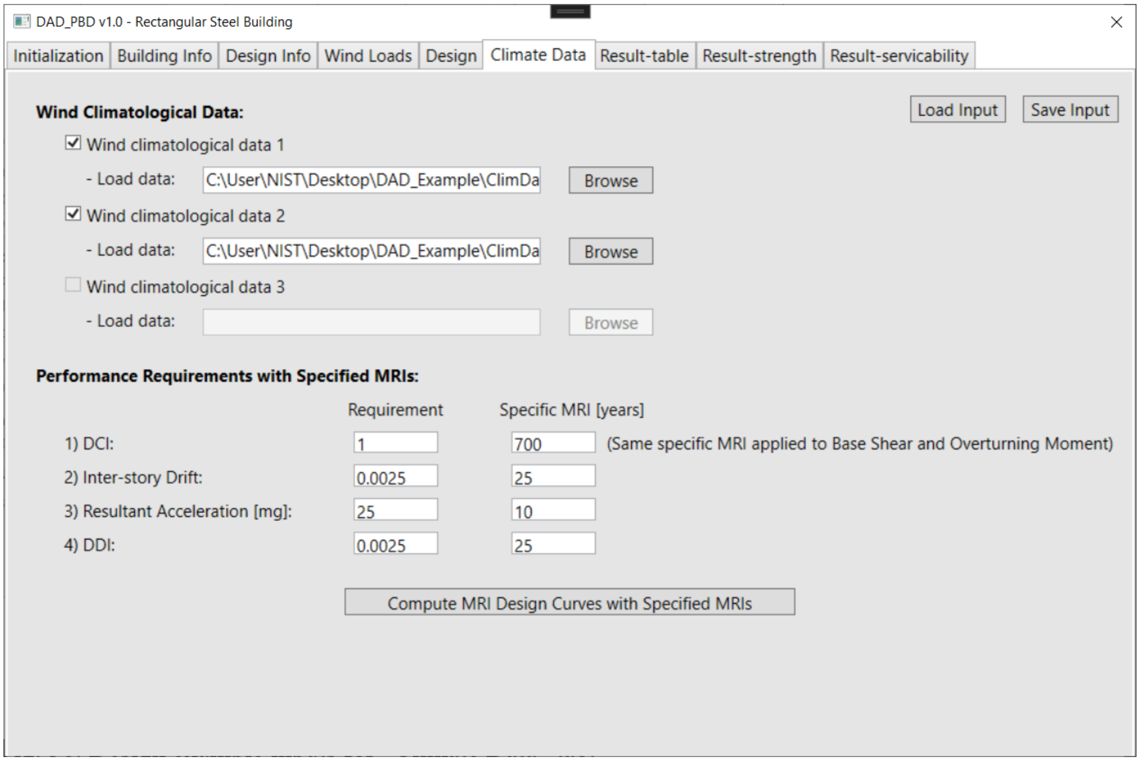
Lower Limit Requirement:

Limiting Value: ● 80% ○ 50% ○ No Limit

ASCE 7-Based Principal Loads:

Overturning Moments (X-Dir) [kN-m]: 2022469.8917 Overturning Moments (Y-Dir) [kN-m]: 1238141.7689

Fig. 35. Design example inputs for “Design” tab.



Wind Climatological Data:

☑ Wind climatological data 1

- Load data: C:\User\NIST\Desktop\DAD_Example\ClimDa

☑ Wind climatological data 2

- Load data: C:\User\NIST\Desktop\DAD_Example\ClimDa

☐ Wind climatological data 3

- Load data:

Performance Requirements with Specified MRIs:

	Requirement	Specific MRI [years]
1) DCI:	1	700 (Same specific MRI applied to Base Shear and Overturning Moment)
2) Inter-story Drift:	0.0025	25
3) Resultant Acceleration [mg]:	25	10
4) DDI:	0.0025	25

Fig. 36. Design example inputs for “Climate Data” tab.

3.7. Design Scenario Results

3.7.1. Dynamic Structural Properties

The first mode of the structure had the highest natural period at 5.77 sec (f_n = 0.173 Hz). The modal periods with corresponding natural frequencies are reported in Table 3, and the mode shapes from ETABS are shown in Fig. 37, where the first two modes are translational in the x- and y-directions, and the third is torsional. Based on the fundamental natural frequency of the building, 25 milli-g was determined as the maximum acceptable acceleration for a 10-year MRI, as recommended by the ATC Design Guide [28] (Fig. 31).

Table 3. Dynamic structural properties.

Mode Number	Periods (sec)	Frequency (Hz)
1	5.765	0.173
2	5.127	0.195
3	2.779	0.360

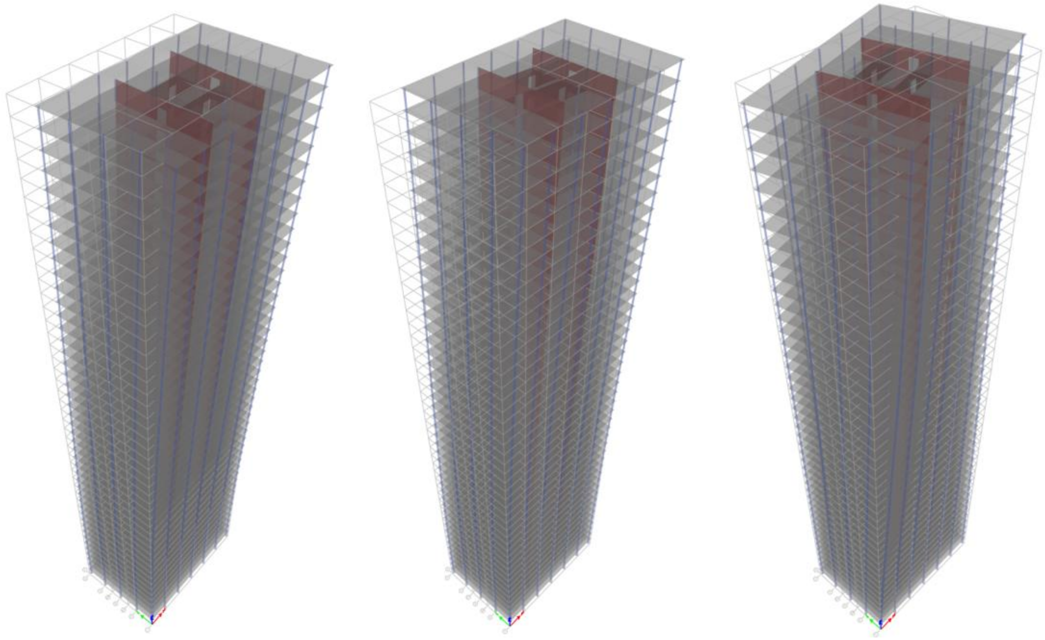


Fig. 37. The first three mode shapes of the RC CAARC building.

3.7.2. DAD Design Results

In this section, the design results of the RC CAARC building are presented. Figures 38-45 show the response surfaces and MRI design curves for various design parameters, including base shear, overturning moment, DCI, inter-story drift ratio, acceleration, and DDI.

The most highly-utilized shear wall in the structure was shear wall “PEb” at Story 1 with a DCI_{PM} of 1.166 for an MRI of 700 years (Fig. 40), which exceeds the acceptance criteria for DCI.

Note that the maximum DCI_{PM} in the response surface also exceeds the DCI requirement (1.0 in this case) at a wind speed of 70 m/s (Fig. 40). This can be attributed to a change in axial force from net compression to net tension. Once the concrete shear wall experiences net tension, minimal bending capacity remains compared to a wall in compression. Note that the legs of the shear wall are modelled separately in ETABS for this example. If the shear wall is modelled as whole, the design results will be different. Link beam "S35" at Story25 had the highest utilization of all designed link beams. The DCI_{VT} of link beam "S35" at Story 16 was 0.715 for 700-MRI (Fig. 41). Most of the first-floor columns had a DCI_{PM} near 0.83 for an MRI of 700 years. The response surface and the MRI design curve of one of the columns (Column #6) are shown in Fig. 42. As indicated in Fig. 42, the DCI of the columns did not increase much over the MRI spectrum, because the majority of the wind load is resisted by the shear wall, and the columns were mostly used to resist the gravity loads.

Figure 46 shows the vertical profiles of the serviceability design parameters for column line "WF01_01" and panel "WF01_01". In general, all three design parameters continuously increased along the height. For the inter-story drift, the drift in the *y*-direction controlled with a maximum inter-story drift ratio of 0.0014, occurring at the 34th floor. The maximum resultant acceleration reached 6 mg at the top floor, while the maximum DDI of 0.00096 occurred on the 40th floor. All serviceability design parameters were well below the acceptance criteria defined in Section 3.1 for all floors.

As demonstrated above, the controlling design parameter was the DCI_{PM} and the RC members of the CAARC building were highly utilized for strength design, where some exceed the design limit and require a re-design. There is also a considerable room for optimization of the serviceability design. For illustration purposes, the RC members in this design example were not iterated or optimized. However, users can perform the re-design by repeating Steps 3-7 in Section 2.1.

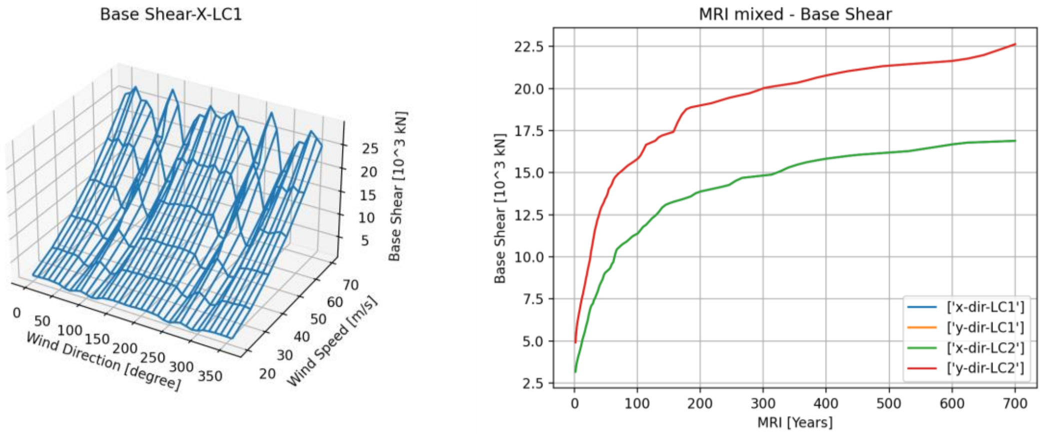


Fig. 38. Base shear response surface (*x*-dir) LC1 (left) and MRI design curve (right).

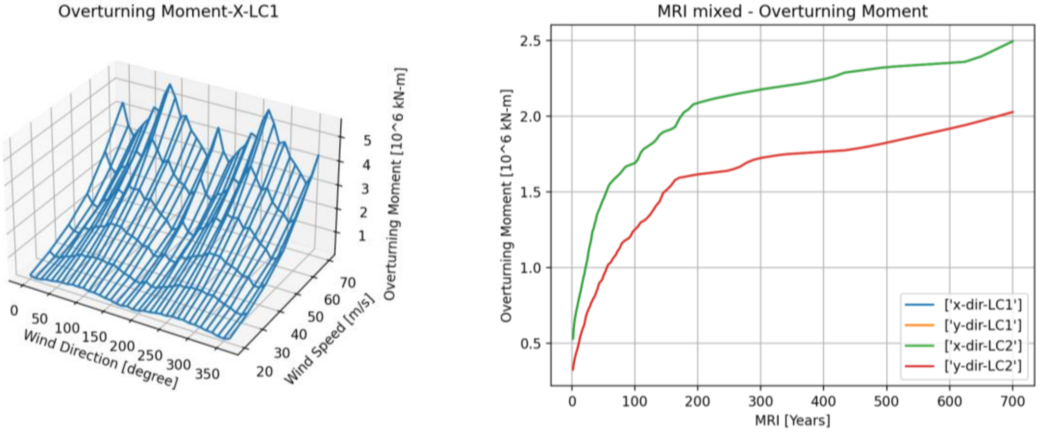


Fig. 39. Overturning moment response surface (*x*-dir) LC1 (left) and MRI design curve (right).

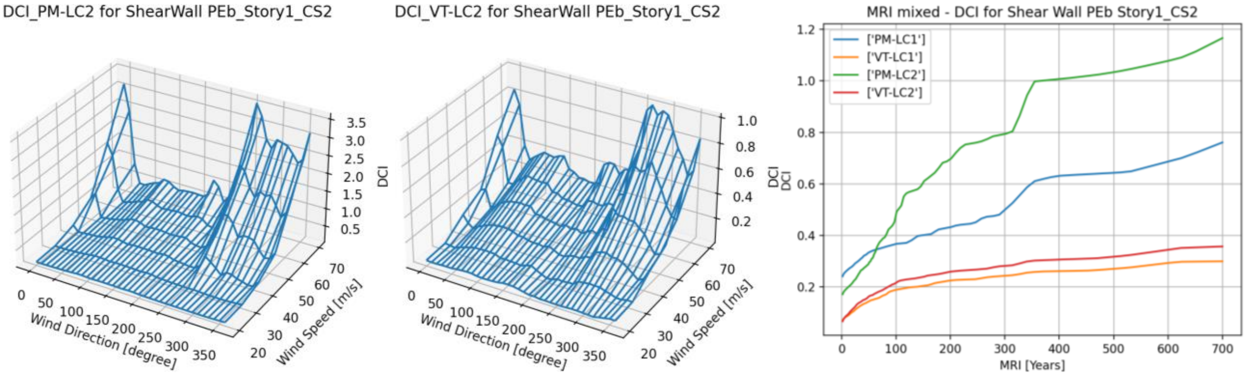


Fig. 40. DCI_{PM} (left) and DCI_{VT} (middle) response surface LC2 and MRI design curve (right) for shear wall PEb – Story1 CS#2.

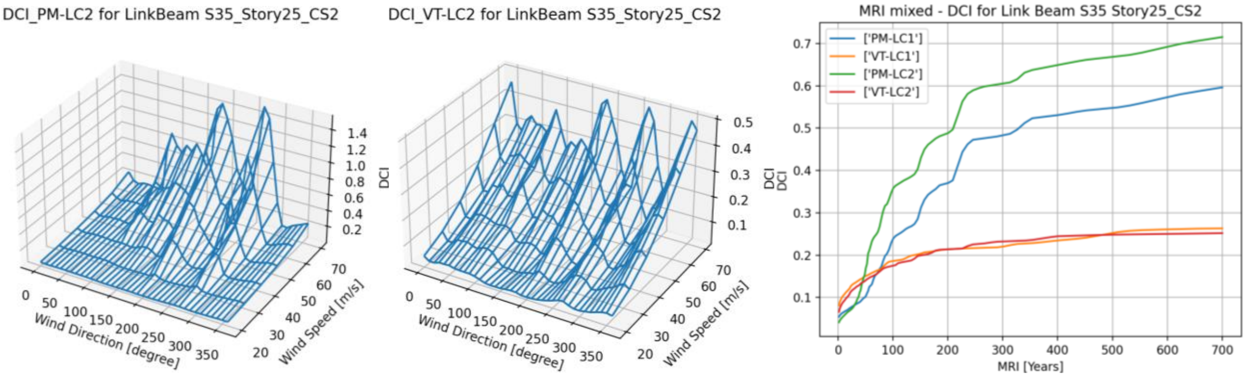


Fig. 41. DCI_{PM} (left) and DCI_{VT} (middle) response surface LC2 and MRI design curve (right) for link beam S35 – Story25 CS#2.

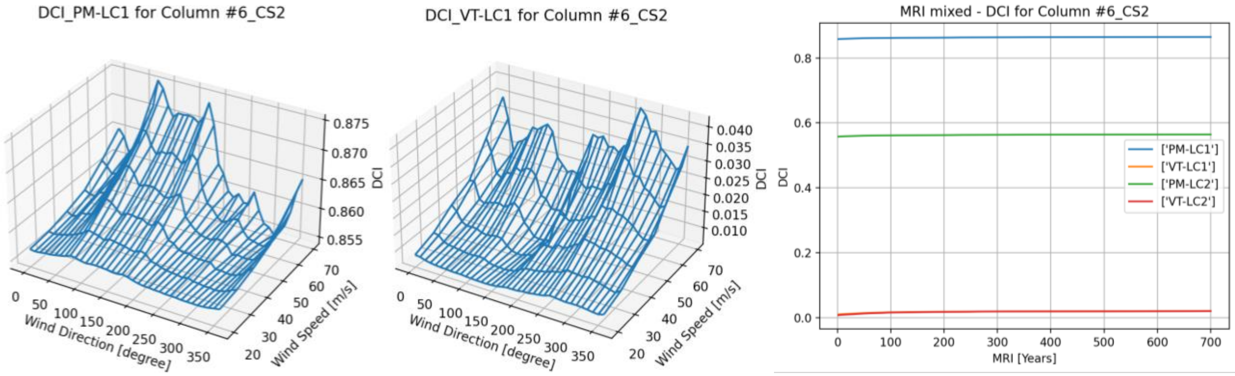


Fig. 42. DCI_{PM} **(left) and** DCI_{VT} **(middle) response surface LC1 and MRI design curve (right) for Column #6 CS#2.**

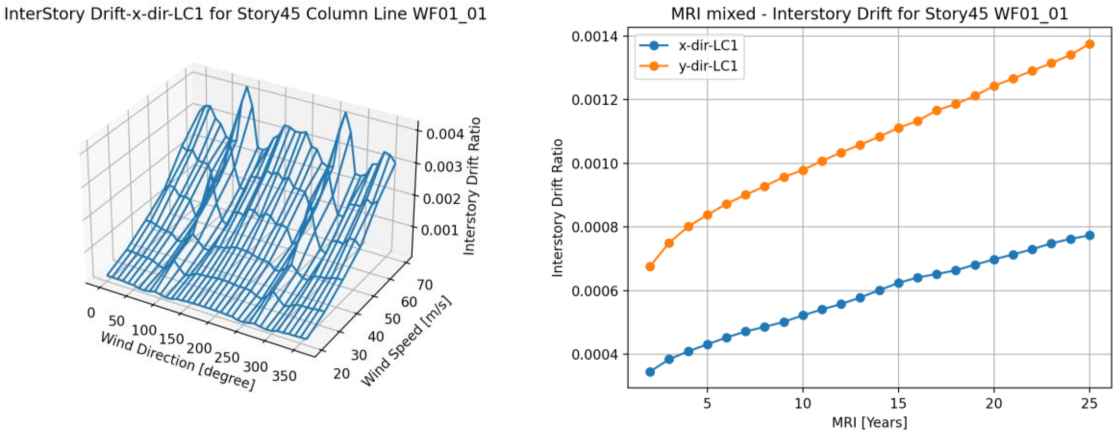


Fig. 43. Inter-story drift ratio response surface (*x*-dir) LC1 (left) and MRI design curve (right) for Column line WF01_01 on the 45th floor.

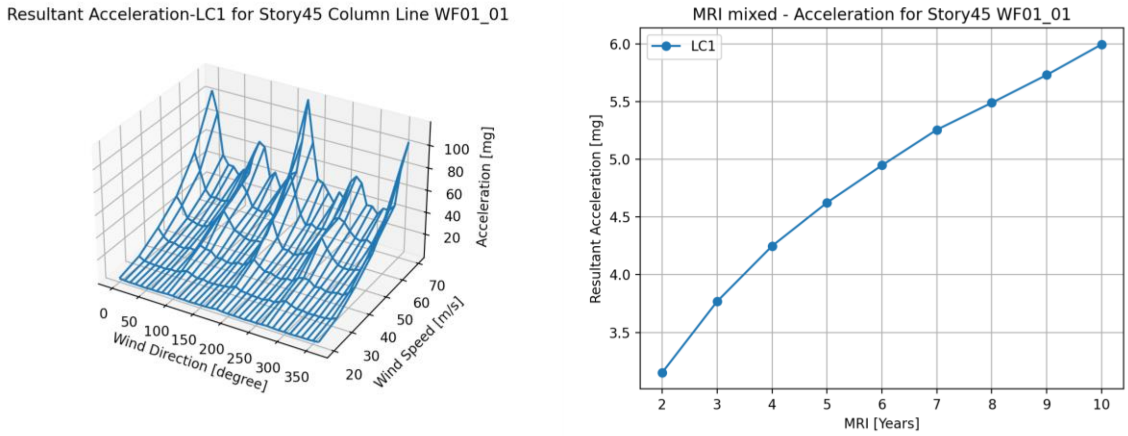


Fig. 44. Acceleration response surface LC1 (left) and MRI design curve (right) for Column line WF01_01 on the 45th floor.

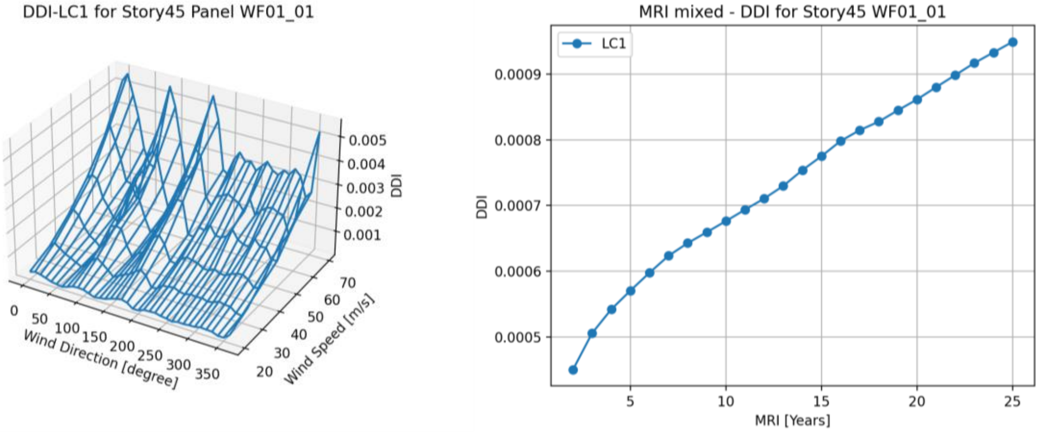


Fig. 45. DDI response surface LC1 (left) and MRI design curve (right) for panel WF01_01 on the 45th floor.

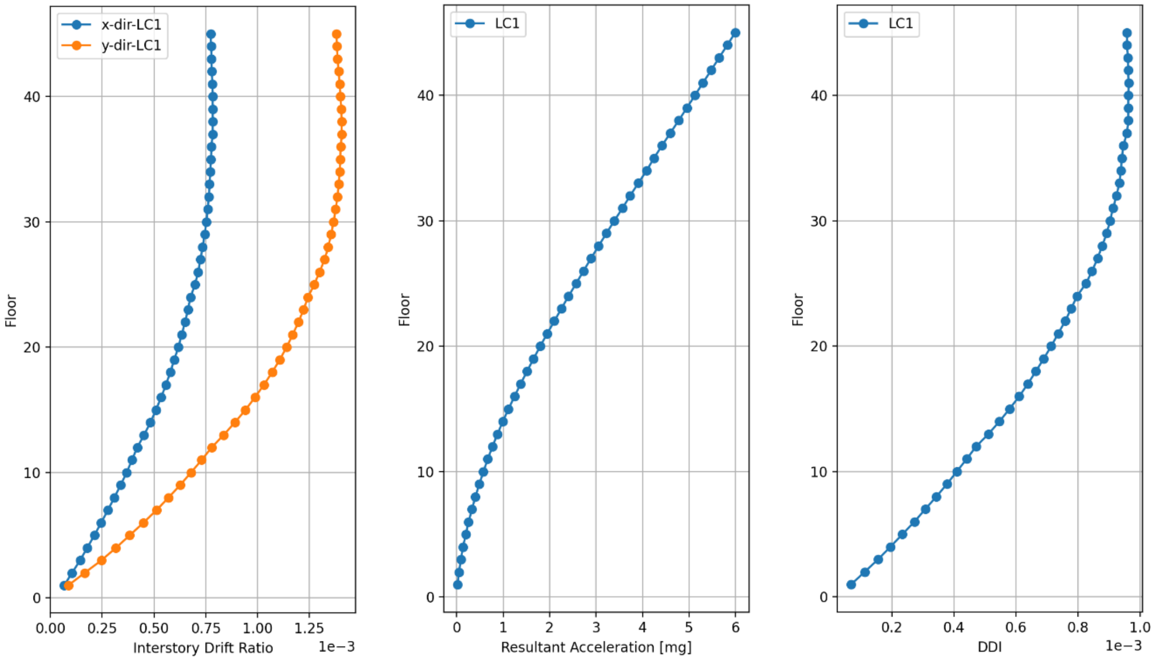


Fig. 46. Inter-story Drift (left), acceleration (center), DDI (right) profile for column line WF01_01 and panel WF01_01.

4. Summary

This report presented the development of DAD_PBD version 2.0, aimed at the practical application of the DAD method in structural engineering, with a focus on Performance-Based Wind Design (PBWD) for high-rise buildings. It also includes a case study demonstrating the design of a 45-story reinforced concrete shear wall building using the DAD_PBD software.

The previous DAD_PBD version 1.0, which utilizes structural analysis software ETABS, was developed to adopt the Python platform for improving computational efficiency and accessibility to structural engineers. It also aimed to enhance the capability of serviceability design by introducing Deformation Damage Index (DDI) as an additional design parameter. However, the software application was limited to only rectangular-shaped buildings with steel-framed members. The new DAD_PBD version presented in this report expands its application to reinforced concrete buildings and irregular-shaped buildings. It features the capability to apply discretely distributed wind loads to the building edges, making it more suitable for irregular-shaped buildings and those with asymmetric structural systems. Additionally, it can design RC members using the commercial design software SpColumn, and significantly reduce the computational cost associated with ETABS by running parallel ETABS analyses on multiple computers.

Future enhancements are projected to further broaden the software's capabilities. These improvements include expansion of the definition of irregular-shaped buildings with more complex geometry, full reliance on structural design software to calculate the design strength of both steel and RC members with more general shapes, and inclusion of the Equivalent Static Wind load (ESWL) method to DAD_PBD. On the structural analysis side, future additions may include live load reduction, modal analysis feature, and integration of non-linear analysis. Additionally, a user-friendly 3D viewer of design parameters is currently under development.

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Appendix A. Format of Data Required for Wind Load Calculation

A.1. Pressure Coefficient (Cp) Data

Pressure coefficient data must be in a MATLAB file (.mat) or HDF5 file (.hdf5) containing the time histories of the pressure coefficients measured at all the taps of a building model. The variable for the C_p time histories must be named “Cp_n”. The file name should adhere to the naming scheme “Cp_XXX”, where the suffix XXX represents the direction of wind (WD) in degrees. For example, “Cp_000.mat” refers to a file that contains the Cp time histories for the wind direction of 0 degrees, while “Cp_180.mat” pertains to the file with the C_p time histories for the wind direction of 180 degrees. The following shows the data structure of the variable “Cp_n”:

Cp_n [No. of data points (n) x No. of pressure taps (m)] =

$$\begin{bmatrix} \mathrm{Cp}_{\mathrm{timestep\ 1,\,tap\,\#\,1}} & \mathrm{Cp}_{\mathrm{timestep\ 1,\,tap\,\#\,2}} & \mathrm{Cp}_{\mathrm{timestep\ 1,\,tap\,\#\,3}} & \cdots & \mathrm{Cp}_{\mathrm{timestep\ 1,\,tap\,\#\,m}} \\ \mathrm{Cp}_{\mathrm{timestep\ 2,\,tap\,\#\,1}} & \mathrm{Cp}_{\mathrm{timestep\ 2,\,tap\,\#\,2}} & \mathrm{Cp}_{\mathrm{timestep\ 2,\,tap\,\#\,3}} & \cdots & \mathrm{Cp}_{\mathrm{timestep\ 2,\,tap\,\#\,m}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathrm{Cp}_{\mathrm{timestep\ n,\,tap\,\#\,1}} & \mathrm{Cp}_{\mathrm{timestep\ n,\,tap\,\#\,2}} & \mathrm{Cp}_{\mathrm{timestep\ n,\,tap\,\#\,3}} & \cdots & \mathrm{Cp}_{\mathrm{timestep\ n,\,tap\,\#\,m}} \end{bmatrix}$$

For example, if pressure coefficient time histories consist of 7504 timesteps for each of 120 pressure taps, the corresponding variable, named “Cp_n”, would be represented by a 7504 × 120 matrix.

A.2. Floor Wind Load Data

Floor wind load data should be stored in CSV files (.csv). These files contain the time histories of the floor loads of the building model determined from the wind tunnel tests or CFD simulations. The files must follow the same format as the CSV files generated using the C_p data. With each file containing one array of corresponding data, the folders and files follow the following format (see Fig. 14):

- Folder: The format of the folder name should be *WD_XXX,* where *XXX* represents the three-digit wind direction. For example, the folder containing the floor wind loads for the 80-degree wind direction should be *WD_080*.
- CVS Files: The format of the CVS file should be *FYYY_XXX_Zz,* where *YYY* is the three-digit floor number, *XXX* is the three-digit wind direction, and *Zz* corresponds to the load type (e.g., F_x, F_y, M_z). For ground floor loads, *FYYY* is replaced with *GF*. For example, the CSV file for floor loads acting in the *y*-direction on the 23rd floor for the 240-degree wind direction and for ground floor moments acting in the *z*-direction for the 60-degree wind direction should be named *F023_240_Fy.csv* and *GF_060_Mz.csv*, respectively.

A.3. Pressure Tap Identification

The pressure tap identification file must be located in a MATLAB file (.mat) or HDF5 file (.hdf5) containing the tap number information of the building model. For each wall face, four variables must be saved, named “WF_1”, “WF_2”, “WF_3”, and “WF_4”. The tap ID file can be saved under any chosen name. The suffixes 1 to 4 represent the building’s face numbers, arranged in the order of south (-y), east (+x), north (+y), and west (-x) sides of the building (refer to Fig. 14). These variables are matrices composed of rows representing the number of taps along the height of the building model (z-direction), and columns representing the number of taps along the width or depth of the building model (x- or y-direction). Each component of this variable represents the tap number. See the example below for illustration.

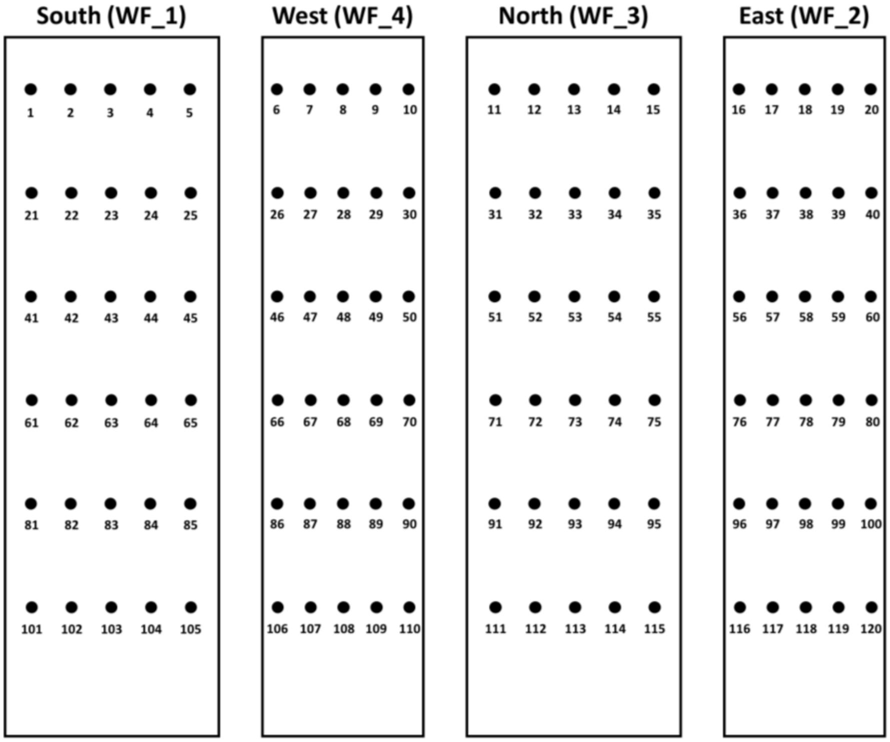


Fig. A-1. Pressure tap locations of the CAARC building model.

WF_3 [No. of taps along height x No. taps along width or depth] =

$$\begin{bmatrix} 11 & 12 & 13 & 14 & 15 \\ 31 & 32 & 33 & 34 & 35 \\ 51 & 52 & 53 & 54 & 55 \\ 71 & 72 & 73 & 74 & 75 \\ 91 & 92 & 93 & 94 & 95 \\ 111 & 112 & 113 & 114 & 115 \end{bmatrix}$$

WF_4 [No. of taps along height x No. taps along width or depth] =

$$\begin{bmatrix} 6 & 7 & 8 & 9 & 10 \\ 26 & 27 & 28 & 29 & 30 \\ 46 & 47 & 48 & 49 & 50 \\ 66 & 67 & 68 & 69 & 70 \\ 86 & 87 & 88 & 89 & 90 \\ 106 & 107 & 108 & 109 & 110 \end{bmatrix}$$

A.4. Pressure Tap Coordinates

The pressure tap coordinate file must be in a MATLAB file (.mat) or HDF5 file (.hdf5) containing the coordinates (x, y, z) of each tap in the model scale. The variable must be named “tap_coord”, but the filename can be saved with an arbitrary name. The variable must be structured as a matrix composed of rows representing the number of taps and four columns corresponding to the sequential number of the tap, its x-, y-, and z-coordinates, respectively. Make sure that the coordinates follow the same unit as the unit defined in the Section 2.4. For example, if SI unit is chosen, the coordinates should be in meters, and if US customary unit is chosen, the coordinates should be in feet.

tap_coord [No. of pressure taps (m) x 4] =

$$\begin{bmatrix} 1 & x_{tap\,\#\,1} & y_{tap\,\#\,1} & z_{tap\,\#\,1} \\ 2 & x_{tap\,\#\,2} & y_{tap\,\#\,2} & z_{tap\,\#\,2} \\ 3 & x_{tap\,\#\,3} & y_{tap\,\#\,3} & z_{tap\,\#\,3} \\ \vdots & \vdots & \vdots & \vdots \\ tap\#\,m & x_{tap\,\#\,m} & y_{tap\,\#\,m} & z_{tap\,\#\,m} \end{bmatrix}$$

Appendix B. Format Required for Climatological Data

The climatological data file must be stored in a MATLAB file (.mat) or HDF5 file (.hdf5), in which the filename can be saved with an arbitrary name. Table B.1 summarizes the variables contained in the extreme directional wind speed data file.

Table B.1. Summary of variables and data format for climatological data

Variable Name	Data Content	Data Type	Data size
lambda_wind	Annual probability of storm occurrence	Float [double]	1 [1,1]
N_wind	Number of storm events	Integer	1 [1,1]
dir_wind	Wind directions of storm events	Array of float [double array]	(No. of directions,) [1, No. of directions]
w_speed	Wind speed matrix	Array of float [double matrix]	(N_wind, No. of directions) [N_wind, No. of directions]
Ratios_Vs	Micro-meteorological data	Array of float [double array]	(4,) [1,4]
terrain	Directional terrain exposures surrounding the building of interest	List of string [Cell array]	37 [1,37]

Note: Data type and size are in Python format; the formats in brackets are in MATLAB.

- Micro-meteorological data (Ratio_Vs)

  The variable “Ratio_Vs” is a row vector containing the ratios between wind speeds at the weather station (e.g., at 10 m above ground in open terrain exposure) and the mean hourly wind speeds at the building height for the requisite terrain exposures. The extreme wind speed analyses must use micro-meteorologically homogeneous data, meaning that all the wind speed data in a set correspond to 1) the same height above ground, 2) with the same terrain exposure (e.g., open or suburban), and 3) the same averaging time (e.g., 3-s, 1-min, 10-min, or 1-hour). If the wind speed data do not satisfy the micrometeorological homogeneity requirements, they should be transformed to satisfy the requirements. To convert them to the mean hourly wind speeds at the building height in the requisite terrain exposure, the wind speed ratios, i.e., the variable “Ratio_Vs”, should be used for each terrain exposure. The variable must consist of four columns with respect to the terrain exposures, as shown below.

$$\mathbf{Ratio\_V_s} = \begin{bmatrix} \underset{\text{Urban}}{\dfrac{V_A^H}{V_C^{10m}}} & \underset{\text{Suburban}}{\dfrac{V_A^H}{V_C^{10m}}} & \underset{\text{Open}}{\dfrac{V_A^H}{V_C^{10m}}} & \underset{\text{Water Surface}}{\dfrac{V_A^H}{V_C^{10m}}} \end{bmatrix}$$

For details refer to the ‘Micro-meteorological data’ section in ‘NIST Hurricane wind speed data’ at www.nist.gov/wind. Note that if the extreme directional wind speed data already meets the micro-meteorological conditions, all values of the “Ratio_Vs” should be set to 1.

- Directional terrain exposures surrounding the building (terrain)

  The variable terrain can be a row vector containing terrain roughness in 37 directions clockwise from 0° to 360° with 10° increments from the North. The terrain exposure is categorized as A, B, C, and D for urban, suburban, open, and unobstructed terrains (water), respectively. The terrain exposure can be different according to directions, which enables DAD_PBD to account for the directionality effects of the terrain exposure. This variable should be made by a cell array for the .mat file or a string list for the .hdf5 file, which has the characters like ‘A’, ‘B’, ‘C’, and ‘D’. Note that if the extreme directional wind speed data already satisfy the micro-meteorological conditions, all values of the terrain should be set to ‘C’. Also, note that the directional terrain exposures surrounding the building should be identical to those used in wind tunnel tests for measurements of the aerodynamic pressure data described in Section 2.5.

Appendix C. Input Data Format

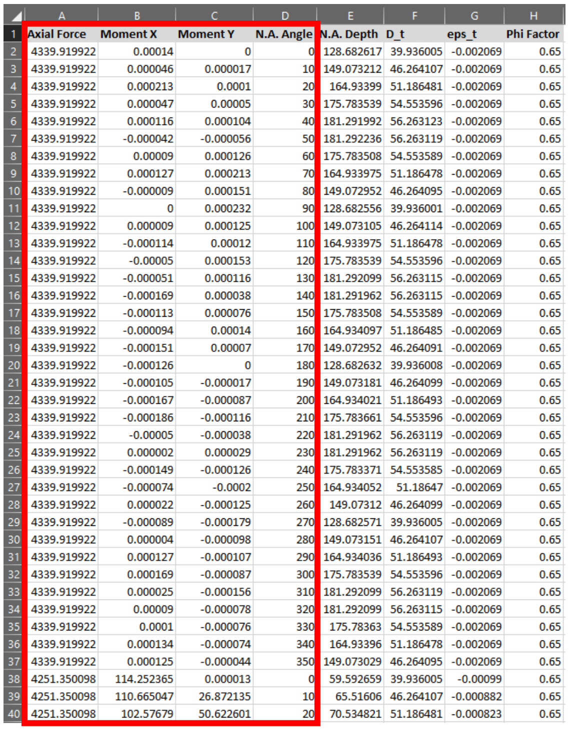
The input data file must be saved in a ".txt" file. For any checkbox, the inputs should be either 1 or 0, where 0 and 1 represent "unchecked" and "checked", respectively. For radio buttons, the inputs should be arranged in order starting from "1", from top to bottom and left to right.

Line #	Content	Line #	Content	Line #	Content
1	Type of Structure	**24**	Wind direction increment	**47**	Beam wind effect neglect
2	Path to ETABS .dll file	**25**	Model scale	**48**	Path to RC schedule
3	Path to EABS model	**26**	Reference wind speed	**49**	DCI checkbox
4	Path to "Save Output"	**27**	Sampling rate	**50**	Base shear checkbox
5	Hide ETABS option	**28**	Floor wind load radio	**51**	Overturning moment checkbox
6	Unit	**29**	Path to Cp data	**52**	Inter-story drift checkbox
7	Building Shape	**30**	Path to tap ID	**53**	Resultant acceleration checkbox
8	# of floors	**31**	Path to tap coordinates	**54**	DDI checkbox
9	Height of the building	**32**	Interpolation method	**55**	ASCE limit radio
10	Building width (top)	**33**	Loading type radio	**56**	ASCE 7 Principal loads Movtn X-dir
11	Building depth (top)	**34**	# of distributed point loads (*x*-dir)	**57**	ASCE 7 Principal loads Movtn Y-dir
12	Building width (bottom)	**35**	# of distributed point loads (*y*-dir)	**58**	Climatological data1 checkbox
13	Building depth (bottom)	**36**	Wind speed LB	**59**	Climatological data2 checkbox
14	X-offset	**37**	Wind speed UB	**60**	Path to climatological data1
15	Y-offset	**38**	Wind speed increment	**61**	Path to climatological data2
16	Orientation	**39**	Peak calculation option	**62**	DCI requirement
17	Analysis type	**40**	# of points discarded	**63**	Inter-story drift ratio requirement
18	Strength load combo	**41**	# of points for MPIT	**64**	Resultant acceleration requirement
19	Serviceability load combo	**42**	Selected member radio	**65**	DDI requirement
20	P-delta: Dead Load	**43**	Unique Name or Group Name	**66**	MRI DCI
21	P-delta: Live Load	**44**	Column line (Acc.)	**67**	MRI Inter-story drift ratio
22	Wind direction LB	**45**	Column line (Disp.)	**68**	MRI Resultant acceleration
23	Wind direction UB	**46**	Panel (DDI)	**69**	MRI DDI

Line #	Content	Line #	Content	Line #	Content
70	Multi-runs for ETABS				
71	Wind speed LB (ETABS Multi-runs)				
72	Wind speed UB (ETABS Multi-runs)				
73	Wind speed increment (ETABS Multi-runs)				

Appendix D. Reinforce Concrete PMM Interaction File Format

The Reinforced Concrete PMM interaction file must be in a CSV file and does not require a specific file name. The CSV file should contain four columns with the following values: 1) axial forces, 2) moment about the x-axis, 3) moment about the y-axis, and 4) neutral axis angle. Figure D.1 demonstrates an example CSV file exported from SpColumn. As shown in the figure, only the first four columns from the left (red box in figure below) are required although the SpColumn and other design software may provide additional variables. The column headers for the four columns must be titled: 1) "Axial Force", 2) "Moment X", 3) "Moment Y", and 4) "N.A. Angle". It is essential that the headers are consistent. Otherwise, the software will not be able to read the CSV files. Note that headers are case-sensitive. The force and length units must be in kN and m for the SI unit system, and kip and ft for US customary unit system. Note that this file format is only required to be used for the RC PMM interaction diagrams in DAD_PBD, regardless of the PMM calculation software.



	A	B	C	D	E	F	G	H
1	**Axial Force**	**Moment X**	**Moment Y**	**N.A. Angle**	**N.A. Depth**	**D_t**	**eps_t**	**Phi Factor**
2	4339.919922	0.00014	0	0	128.682617	39.936005	-0.002069	0.65
3	4339.919922	0.000046	0.000017	10	149.073212	46.264107	-0.002069	0.65
4	4339.919922	0.000213	0.0001	20	164.93399	51.186481	-0.002069	0.65
5	4339.919922	0.000047	0.00005	30	175.783539	54.553596	-0.002069	0.65
6	4339.919922	0.000116	0.000104	40	181.291992	56.263123	-0.002069	0.65
7	4339.919922	-0.000042	-0.000056	50	181.292236	56.263119	-0.002069	0.65
8	4339.919922	0.00009	0.000126	60	175.783508	54.553589	-0.002069	0.65
9	4339.919922	0.000127	0.000213	70	164.933975	51.186478	-0.002069	0.65
10	4339.919922	-0.000009	0.000151	80	149.072952	46.264095	-0.002069	0.65
11	4339.919922	0	0.000232	90	128.682556	39.936001	-0.002069	0.65
12	4339.919922	0.000009	0.000125	100	149.073105	46.264114	-0.002069	0.65
13	4339.919922	-0.000114	0.00012	110	164.933975	51.186478	-0.002069	0.65
14	4339.919922	-0.00005	0.000153	120	175.783539	54.553596	-0.002069	0.65
15	4339.919922	-0.000051	0.000116	130	181.292099	56.263115	-0.002069	0.65
16	4339.919922	-0.000169	0.000038	140	181.291962	56.263115	-0.002069	0.65
17	4339.919922	-0.000113	0.000076	150	175.783508	54.553589	-0.002069	0.65
18	4339.919922	-0.000094	0.00014	160	164.934097	51.186485	-0.002069	0.65
19	4339.919922	-0.000151	0.00007	170	149.072952	46.264091	-0.002069	0.65
20	4339.919922	-0.000126	0	180	128.682632	39.936008	-0.002069	0.65
21	4339.919922	-0.000105	-0.000017	190	149.073181	46.264099	-0.002069	0.65
22	4339.919922	-0.000167	-0.000087	200	164.934021	51.186493	-0.002069	0.65
23	4339.919922	-0.000186	-0.000116	210	175.783661	54.553596	-0.002069	0.65
24	4339.919922	-0.00005	-0.000038	220	181.291962	56.263119	-0.002069	0.65
25	4339.919922	0.000002	0.000029	230	181.291962	56.263119	-0.002069	0.65
26	4339.919922	-0.000149	-0.000126	240	175.783371	54.553585	-0.002069	0.65
27	4339.919922	-0.000074	-0.0002	250	164.934052	51.18647	-0.002069	0.65
28	4339.919922	0.000022	-0.000125	260	149.07312	46.264099	-0.002069	0.65
29	4339.919922	-0.000089	-0.000179	270	128.682571	39.936005	-0.002069	0.65
30	4339.919922	0.000004	-0.000098	280	149.073151	46.264107	-0.002069	0.65
31	4339.919922	0.000127	-0.000107	290	164.934036	51.186493	-0.002069	0.65
32	4339.919922	0.000169	-0.000087	300	175.783539	54.553596	-0.002069	0.65
33	4339.919922	0.000025	-0.000156	310	181.292099	56.263119	-0.002069	0.65
34	4339.919922	0.00009	-0.000078	320	181.292099	56.263115	-0.002069	0.65
35	4339.919922	0.0001	-0.000076	330	175.78363	54.553589	-0.002069	0.65
36	4339.919922	0.000134	-0.000074	340	164.93396	51.186478	-0.002069	0.65
37	4339.919922	0.000125	-0.000044	350	149.073029	46.264095	-0.002069	0.65
38	4251.350098	114.252365	0.000013	0	59.592659	39.936005	-0.00099	0.65
39	4251.350098	110.665047	26.872135	10	65.51606	46.264107	-0.000882	0.65
40	4251.350098	102.57679	50.622601	20	70.534821	51.186481	-0.000823	0.65

Fig. D-1. CSV export example of SpColumn.

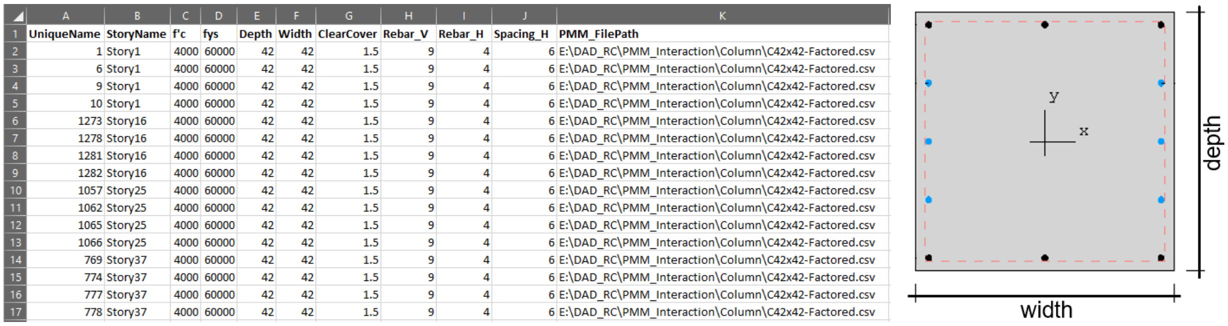
Appendix E. Reinforce Concrete Schedule Format

The Reinforced Concrete (RC) schedule file must be in an Excel file and requires a specific file name: 1) “Column_Schedule.xlsx” for columns, 2) “ShearWall_Schedule.xlsx” for shear walls, and 3) “LinkBeam_Schedule.xlsx” for link beams. The Excel files must contain the dimensions and all related concrete and rebar information. The unit system must be consistent with the unit system chosen in the DAD_PBD software. Note that the link beams are referred to as spandrels in ETABS. See the following for specific variables for specific RC member.

1) For the column schedule, the “Column_Schedule.xlsx” file must contain the following values with corresponding headers:

	Variable	**Headers**	**Unit**
1)	Unique name of column member	UniqueName	N/A
2)	Story name of column member	StoryName	N/A
3)	Concrete compressive strength	f’c	psi or kPa
4)	Steel yield strength	fys	psi or kPa
5)	Depth	Depth	in or cm
6)	Width	Width	in or cm
7)	Clear cover	ClearCover	in or cm
8)	Vertical rebar size	Rebar_V	N/A
9)	Horizontal rebar size	Rebar_H	N/A
10)	Horizontal rebar spacing	Spacing_H	in or cm
11)	Directory to PMM file	PMM_FilePath	N/A

An example of the RC schedule for column and the column cross-section is shown below.



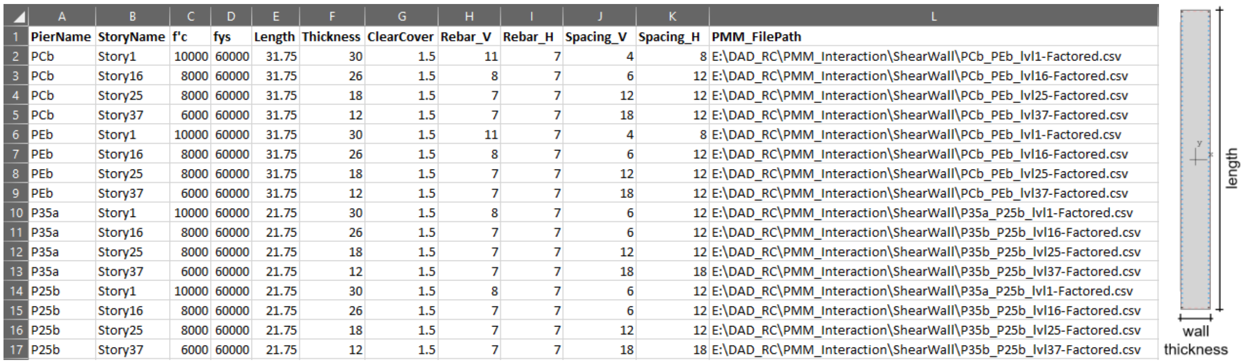
	A	B	C	D	E	F	G	H	I	J	K
1	UniqueName	StoryName	f'c	fys	Depth	Width	ClearCover	Rebar_V	Rebar_H	Spacing_H	PMM_FilePath
2	1	Story1	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
3	6	Story1	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
4	9	Story1	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
5	10	Story1	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
6	1273	Story16	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
7	1278	Story16	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
8	1281	Story16	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
9	1282	Story16	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
10	1057	Story25	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
11	1062	Story25	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
12	1065	Story25	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
13	1066	Story25	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
14	769	Story37	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
15	774	Story37	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
16	777	Story37	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv
17	778	Story37	4000	60000	42	42	1.5	9	4	6	E:\DAD_RC\PMM_Interaction\Column\C42x42-Factored.csv

Fig. E-1. Example of RC column schedule and the column cross-section.

2) For the shear wall schedule, the “ShearWall_Schedule.xlsx” file must contain the following values with corresponding headers:

	Variable	Headers	Unit
1)	Pier label (ETABS) of shear wall	PierName	N/A
2)	Story name of shear wall member	StoryName	N/A
3)	Concrete compressive strength	f’c	psi or kPa
4)	Steel yield strength	fys	psi or kPa
5)	Length of shear wall	Length	ft or m
6)	Wall thickness of shear wall	Thickness	in or cm
7)	Clear cover	ClearCover	in or cm
8)	Vertical rebar size	Rebar_V	N/A
9)	Horizontal rebar size	Rebar_H	N/A
10)	Vertical rebar spacing	Spacing_V	in or cm
11)	Horizontal rebar spacing	Spacing_H	in or cm
12)	Directory to PMM file	PMM_FilePath	N/A

An example of the RC schedule for shear wall and the shear wall cross-section is shown below.



	A	B	C	D	E	F	G	H	I	J	K	L
1	PierName	StoryName	f'c	fys	Length	Thickness	ClearCover	Rebar_V	Rebar_H	Spacing_V	Spacing_H	PMM_FilePath
2	PCb	Story1	10000	60000	31.75	30	1.5	11	7	4	8	E:\DAD_RC\PMM_Interaction\ShearWall\PCb_PEb_lvl1-Factored.csv
3	PCb	Story16	8000	60000	31.75	26	1.5	8	7	6	12	E:\DAD_RC\PMM_Interaction\ShearWall\PCb_PEb_lvl16-Factored.csv
4	PCb	Story25	8000	60000	31.75	18	1.5	7	7	12	12	E:\DAD_RC\PMM_Interaction\ShearWall\PCb_PEb_lvl25-Factored.csv
5	PCb	Story37	6000	60000	31.75	12	1.5	7	7	18	12	E:\DAD_RC\PMM_Interaction\ShearWall\PCb_PEb_lvl37-Factored.csv
6	PEb	Story1	10000	60000	31.75	30	1.5	11	7	4	8	E:\DAD_RC\PMM_Interaction\ShearWall\PCb_PEb_lvl1-Factored.csv
7	PEb	Story16	8000	60000	31.75	26	1.5	8	7	6	12	E:\DAD_RC\PMM_Interaction\ShearWall\PCb_PEb_lvl16-Factored.csv
8	PEb	Story25	8000	60000	31.75	18	1.5	7	7	12	12	E:\DAD_RC\PMM_Interaction\ShearWall\PCb_PEb_lvl25-Factored.csv
9	PEb	Story37	6000	60000	31.75	12	1.5	7	7	18	12	E:\DAD_RC\PMM_Interaction\ShearWall\PCb_PEb_lvl37-Factored.csv
10	P35a	Story1	10000	60000	21.75	30	1.5	8	7	6	12	E:\DAD_RC\PMM_Interaction\ShearWall\P35a_P25b_lvl1-Factored.csv
11	P35a	Story16	8000	60000	21.75	26	1.5	7	7	6	12	E:\DAD_RC\PMM_Interaction\ShearWall\P35b_P25b_lvl16-Factored.csv
12	P35a	Story25	8000	60000	21.75	18	1.5	7	7	12	12	E:\DAD_RC\PMM_Interaction\ShearWall\P35b_P25b_lvl25-Factored.csv
13	P35a	Story37	6000	60000	21.75	12	1.5	7	7	18	18	E:\DAD_RC\PMM_Interaction\ShearWall\P35b_P25b_lvl37-Factored.csv
14	P25b	Story1	10000	60000	21.75	30	1.5	8	7	6	12	E:\DAD_RC\PMM_Interaction\ShearWall\P35a_P25b_lvl1-Factored.csv
15	P25b	Story16	8000	60000	21.75	26	1.5	7	7	6	12	E:\DAD_RC\PMM_Interaction\ShearWall\P35b_P25b_lvl16-Factored.csv
16	P25b	Story25	8000	60000	21.75	18	1.5	7	7	12	12	E:\DAD_RC\PMM_Interaction\ShearWall\P35b_P25b_lvl25-Factored.csv
17	P25b	Story37	6000	60000	21.75	12	1.5	7	7	18	18	E:\DAD_RC\PMM_Interaction\ShearWall\P35b_P25b_lvl37-Factored.csv

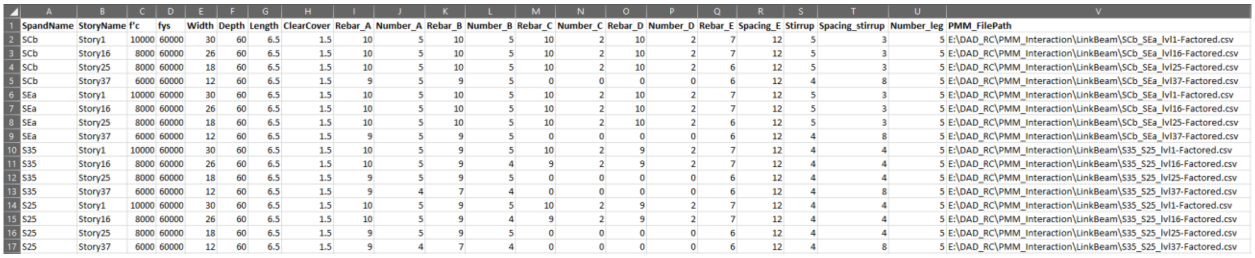
Fig. E-2. Example of RC shear wall schedule and the shear wall cross-section.

3) For the link beam schedule, the “LinkBeam_Schedule.xlsx” file must contain the following values with corresponding headers:

	Variable	Headers	Unit
1)	Spandrel name (ETABS) of link beam	SpandName	N/A
2)	Story name of link beam member	StoryName	N/A
3)	Concrete compressive strength	f’c	psi or kPa
4)	Steel yield strength	fys	psi or kPa
5)	Width	Width	in or cm
6)	Depth	Depth	in or cm

7) Length of link beam	Length	ft or m
8) Clear cover	ClearCover	in or cm
9) A rebar size	Rebar_A	N/A
10) Number of A rebars	Number_A	N/A
11) B rebar size	Rebar_B	N/A
12) Number of B rebars	Number_B	N/A
13) C rebar size	Rebar_C	N/A
14) Number of C rebars	Number_C	N/A
15) D rebar size	Rebar_D	N/A
16) Number of D rebars	Number_D	N/A
17) E rebar size (on each face)	Rebar_E	N/A
18) E rebar max spacing	Spacing_E	in or cm
19) Stirrup size	Stirrup	N/A
20) Stirrup spacing	Spacing_stirrup	in or cm
21) Number of legs in stirrup	Number_leg	N/A
22) Directory to PMM file	PMM_FilePath	N/A

An example of the RC schedule for the link beam and the link beam cross-section is shown below.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	SpandName	StoryName	f'c	fys	Width	Depth	Length	ClearCover	Rebar_A	Number_A	Rebar_B	Number_B	Rebar_C	Number_C	Rebar_D	Number_D	Rebar_E	Spacing_E	Stirrup	Spacing_stirrup	Number_leg	PMM_FilePath
2	SCb	Story1	10000	60000	30	60	6.5	1.5	10	5	10	5	10	2	10	2	7	12	5	3	5	E:\DAD_RC\PMM_Interaction\LinkBeam\SCb_SEa_lvl1-Factored.csv
3	SCb	Story16	8000	60000	26	60	6.5	1.5	10	5	10	5	10	2	10	2	7	12	5	3	5	E:\DAD_RC\PMM_Interaction\LinkBeam\SCb_SEa_lvl16-Factored.csv
4	SCb	Story25	8000	60000	18	60	6.5	1.5	10	5	10	5	10	2	10	2	6	12	5	3	5	E:\DAD_RC\PMM_Interaction\LinkBeam\SCb_SEa_lvl25-Factored.csv
5	SCb	Story37	6000	60000	12	60	6.5	1.5	9	5	9	5	0	0	0	0	6	12	4	8	5	E:\DAD_RC\PMM_Interaction\LinkBeam\SCb_SEa_lvl37-Factored.csv
6	SEa	Story1	10000	60000	30	60	6.5	1.5	10	5	10	5	10	2	10	2	7	12	5	3	5	E:\DAD_RC\PMM_Interaction\LinkBeam\SCb_SEa_lvl1-Factored.csv
7	SEa	Story16	8000	60000	26	60	6.5	1.5	10	5	10	5	10	2	10	2	7	12	5	3	5	E:\DAD_RC\PMM_Interaction\LinkBeam\SCb_SEa_lvl16-Factored.csv
8	SEa	Story25	8000	60000	18	60	6.5	1.5	10	5	10	5	10	2	10	2	6	12	5	3	5	E:\DAD_RC\PMM_Interaction\LinkBeam\SCb_SEa_lvl25-Factored.csv
9	SEa	Story37	6000	60000	12	60	6.5	1.5	9	5	9	5	0	0	0	0	6	12	4	8	5	E:\DAD_RC\PMM_Interaction\LinkBeam\SCb_SEa_lvl37-Factored.csv
10	S35	Story1	10000	60000	30	60	6.5	1.5	10	5	9	5	10	2	9	2	7	12	4	4	5	E:\DAD_RC\PMM_Interaction\LinkBeam\S35_S25_lvl1-Factored.csv
11	S35	Story16	8000	60000	26	60	6.5	1.5	10	5	9	4	9	2	9	2	7	12	4	4	5	E:\DAD_RC\PMM_Interaction\LinkBeam\S35_S25_lvl16-Factored.csv
12	S35	Story25	8000	60000	18	60	6.5	1.5	9	5	9	5	0	0	0	0	6	12	4	4	5	E:\DAD_RC\PMM_Interaction\LinkBeam\S35_S25_lvl25-Factored.csv
13	S35	Story37	6000	60000	12	60	6.5	1.5	9	4	7	4	0	0	0	0	6	12	4	8	5	E:\DAD_RC\PMM_Interaction\LinkBeam\S35_S25_lvl37-Factored.csv
14	S25	Story1	10000	60000	30	60	6.5	1.5	10	5	9	5	10	2	9	2	7	12	4	4	5	E:\DAD_RC\PMM_Interaction\LinkBeam\S35_S25_lvl1-Factored.csv
15	S25	Story16	8000	60000	26	60	6.5	1.5	10	5	9	4	9	2	9	2	7	12	4	4	5	E:\DAD_RC\PMM_Interaction\LinkBeam\S35_S25_lvl16-Factored.csv
16	S25	Story25	8000	60000	18	60	6.5	1.5	9	5	9	5	0	0	0	0	6	12	4	4	5	E:\DAD_RC\PMM_Interaction\LinkBeam\S35_S25_lvl25-Factored.csv
17	S25	Story37	6000	60000	12	60	6.5	1.5	9	4	7	4	0	0	0	0	6	12	4	8	5	E:\DAD_RC\PMM_Interaction\LinkBeam\S35_S25_lvl37-Factored.csv

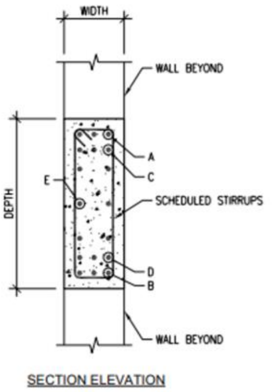


Fig. E-3. Example of RC link beam schedule and the link beam cross-section.