Implementation of AASHTO Wind Load Provisions in Design-Oriented Bridge Finite Element Analysis Software

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Abstract

Bridges must be designed to resist a variety of load types, including loads that arise due to wind. The objective of this research was to develop resources for automated generation of wind loads in design-oriented bridge finite element analysis (FEA) software, based on the 8th Ed. of the *American Association of State Highway and Transportation Officials* (*AASHTO) LRFD Bridge Design Specifications*. Particular emphasis was placed on provisions listed in Sec. 3.4 and Sec. 3.8 of the *AASHTO* specifications, where these sections underwent substantial modifications relative to prior editions. Major efforts of the current research consisted of: 1) Identification of pertinent modifications to the *AASHTO* provisions for quantifying wind loads on bridges; 2) Critical analysis of current wind load generation capabilities in a selected design-oriented bridge FEA software package; 3) Development of templates for new User Interface (UI) components given extant limitations in the program capabilities; and, 4) Documentation of a sample set of programmatic *AASHTO* wind load calculations as part of a case study. As outcomes of this research, developers of the selected FEA software will be equipped with resources (related to both the interface and engineering calculations) to implement new program features for automated generation of wind loads in accordance with the *AASHTO* 8th Ed. specifications.

Introduction

Structural engineers must be able to account for accurate wind loads when designing physical infrastructure so as to uphold structural safety and serviceability requirements. Wind provisions for buildings are frequently updated in design specification documents such as the *American Society of Civil Engineers (ASCE) Minimum Design Loads for Buildings and Other Structures*, which influence aspects of the wind provisions pertaining to bridge structures, as given in the *American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specification*s. With the ever-increasing complexity of structural design specifications, design-oriented computer modeling and automation of processes such as load generation and routine design checks have become pervasive in practice.

Since the early 2000s, the Bridge Software Institute (BSI) at the University of Florida (UF) has maintained and developed design-oriented bridge analysis software (called FB-MultiPier), from which multiple-pier bridge structures can be modeled and analyzed based on parametric input. Included among the available features in FB-MultiPier are those that facilitate generation of the various load types and load combinations delineated in commonly used bridge design provisions. In particular, the software contains dedicated dialogs and engineering-calculation routines, which are collectively intended to encompass the wind load provisions in the *AASHTO LRFD Bridge Design Specifications.*

In previous editions of design specifications put forth by *AASHTO* (e.g., the 6th Ed., *AASHTO* 2012), provisions dedicated to wind loading were based on the fastest-mile wind speed at a given geographic location, which was averaged at different lengths of time. However, in the most recent edition of the *AASHTO* specifications (the 8th Ed., AASHTO 2017), the wind provisions were updated to use a 3-second gust wind speed. These wind speeds were based on many years of ongoing research of applied wind loads on structures (Wassef & Ragget, 2014).

Soon after the release of the *AASHTO* 8th Ed. Specifications (AASHTO 2017), the need to critically assess program capabilities related to wind loading in FB-MultiPier was recognized. As documented herein, the most currently available version of FB-MultiPier (v5.4) could be made consistent with the *AASHTO* 8th Ed. Specifications by taking into account phenomena such as: the effects of the drag coefficient, the 3-second gust wind speed, wind exposure categories, ground surface roughness categories, updated wind pressure equation, gust effect factor, and the pressure exposure and elevation coefficient. To help incorporate such phenomena and to facilitate enhancements of the wind load generation features for bridge design against wind loading in FB-MultiPier, templates were developed for a new series of program dialogs. In addition, a case study was carried out to establish a programmatic set of wind load calculations, and thereby provide a complementary resource to the proposed graphical elements.

Upon implementation of these newly developed dialogs in FB-MultiPier (and the supporting wind load calculations), the software will enable bridge engineers to design more accurately based on geographic location and wind conditions, which in turn, will improve the safety and longevity of future bridges. Future implementation of the resources developed herein will also allow for the production of more economic designs by preventing engineers from making use of over-conservative wind loads in certain cases.

Objectives

The primary objective of this research was to develop new interface and engineering-calculation resources for modifying the wind load generation feature set in FB-MultiPier (where this feature set is referred to as the "wind load generator"). The basis for all newly created program resources was that of the *AASHTO* wind provisions detailed in Sec. 3.4 and Sec. 3.8. A review of the current *AASHTO* wind load provisions, extant FB-MultiPier capabilities, and proposed FB-MultiPier enhancements are discussed in the sections below. In addition, a case study (detailed in Appendix A) was included in this work to exemplify typical wind load calculation procedures.

Scope of work

The scope of work for this study included:

- Wind Engineering: The wind effects on structures and why the wind provisions needed to be improved helped determine what parts of the wind provision should be implemented into the Wind Load Generator.
- *AASHTO* Wind Provisions: Analyzed the updated wind provisions and how wind loads are calculated to identify what needed to be added into the FB-MultiPier Wind Load Generator.
- User Interface (UI) Design: Several new dialogs were developed, with considerations for ease-of-use by practicing engineers.
- Case Study: Mathcad was used to create a step-by-step procedure detailing the wind load calculations based on the current *AASHTO* wind provisions.

Section 1: Overview of Wind Effects on Structures and the Role of Design-Oriented Bridge Finite Element Analysis Software

Structures must be designed to withstand effects due to wind. This requirement holds particular significance for bridges, given that modern structural engineering has allowed for bridge designs to become lighter, more flexible, and less damped relative to more historic designs. Relevant wind engineering topics that influence structural design of bridges include wind micrometeorology issues, extreme wind climatology, aerodynamics and wind tunnel testing, and aeroelasticity (Simiu & Miyata, 2006). Wind climatology provides designers (and entities that publish design specifications) with information on extreme winds that could affect structure throughout their life-cycles (Simiu & Scanlan, 1996).

The level of sophistication required for designing bridges to resist wind loads depends on the bridge configuration. For example, long-span bridges must undergo aeroelastic wind tunnel testing due to relatively pronounced levels of flexibility and susceptibility to aerodynamic instability which include lateral-buckling, vortex-induced oscillation, flutter, and buffeting

(Simiu & Scanlan, 1996). For certain other bridge structures, structural engineers are able to calculate loads that arise due to wind effects by making use of aerodynamic data from wind tunnel tests and of extreme wind speed data, which are publicly available or provided by wind climatology experts.

In contrast to design considerations for long-span bridges, and in regards to wind loading, typical highway bridges are commonly designed via direct application of prescriptive methods documented in design specifications. Nonetheless, it is crucial for structural engineers to understand the reasoning behind specifications such as the *AASHTO* wind load provisions, and how to apply the provisions in adequately accounting for wind load effects during the bridge design process. The *AASHTO* wind load provisions (which pertain to bridge, not building, design) were derived from the *ASCE Minimum Design Loads for Buildings and Other Structures*, but adapted to meet the requirements for bridge design.

Given the above, feature sets in design-oriented bridge finite element analysis (FEA) software must remain up-to-date with respect to commonly used design specifications; paths of execution for the feature sets must be visually organized to reflect the prescriptive procedures set forth in the design specifications; and, critically, the scope of these features should be relevant to the types of bridge structures that are commonly modeled in the software. For the design-oriented bridge FEA software FB-MultiPier, the types of bridges and substructures modeled are generally those of typical highway bridges. Further, when engineers design bridge models using FB-MultiPier, the prescriptive provisions given in the *AASHTO* specifications are generally sufficient for satisfying design requirements. Accordingly, engineers that make use of FB-MultiPier do not have to perform tasks such as manually altering wind speeds to control wind-induced motions caused by aerodynamic instability.

Stated alternatively, bridges designed using FB-MultiPier are typically not deemed to be wind sensitive, meaning that requisite span-to-depth ratios do not exceed 30, the bridges and substructures are not cable-supported, and fundamental vertical or translational periods are not greater than 1 second (AASHTO, 2017). Should a given bridge meet those criteria, then the bridge would be deemed wind-sensitive, and the force effects of wind-induced vibrations must be taken into the consideration in the design process. For this latter scenario, tools other than FB-MultiPier would be utilized, and structure-specific wind studies based on wind tunnel testing would be required.

Section 2: AASHTO 8th Ed. Wind Provisions for Bridge Design

The AASHTO 8th Ed. wind load provisions were developed as part of research prepared for *AASHTO* and funded by the National Cooperative Highway Research Program (NCHRP). For provisions that were applicable to typical highway bridges, wind effects were divided into those originating due to wind pressures acting on the substructure, those acting on the superstructure, and those acting on live load transiting the bridge. In this context, wind loads on the superstructure were the algebraic transverse and longitudinal components of the wind load originating at the superstructure, which can be concentrated and modeled as loads acting on the bearings of bridge substructures. Wind loads from the superstructure for various wind angles were taken as the product of the skew coefficient in Table 3.8.1.2.3a.1 of the *AASHTO* provisions, the wind pressure previously calculated, and the depth of the bridge. Loads applied directly to the substructure were determined based on the transverse and longitudinal forces applied by the wind pressure calculated by a wind pressure equation (discussed below).

Section 2.1: Design Wind Speed

The most significant change that affected the Wind Load Generator feature set in FB-MultiPier drew from the fact that the fastest-mile wind speed was no longer used in design, but instead, wind pressures were based on 3-second gust wind speeds (the 3-second gust wind speed is averaged over 3 seconds). Geographical distributions of the associated design wind speeds were provided in design specifications using contour maps. As an example, **Figure *1***, taken from *ASCE 7-10* (ASCE, 2014), shows the design wind speed at an elevation of 33 ft, for wind exposure Category C, and with a Mean Recurrence Interval (MRI) of 700 years (AASHTO, 2017).

Due to this change in the *AASHTO* wind load provisions, the load factors were modified. For example, the load type Wind on Structure (WS) was reduced from 1.4 to 1.0 (in the Strength III load combination). For special wind regions in the *ASCE 7-10* (**Figure *1***), owners were required to choose the 3-second gust wind speed (V), which was increased based on findings from site-specific wind studies. These studies demonstrated that greater wind speeds than those previously used in design could occur based on a 7% probability of exceedance in 50 years at the selected bridge location (AASHTO, 2017).

In addition to the above modifications, the *AASHTO* 8th Ed. specifications also included a new table, distinguishing wind load considerations for several different load combinations: Strength II, Strength V, Service I, and Service IV. Whereas determination of the Strength III load combination wind speed was relegated as being selected from a wind speed map (e.g., **Figure *1***), Strength V was limited to 80 mph, Service I was limited to 70 mph, and Service IV was limited to 0.75 of the design wind speed used for the Strength III limit state. However, in special wind regions, the bridge owners were required to develop their own policy for the 3-second gust wind speed.

Section 2.2: Wind Exposure Category

Also, the *AASHTO* 8th Ed. specifications introduced a wind exposure category section that must be determined, and which depended on the ground roughness categories defined (*ibid*, Sec. 3.8.1.1.4). It was found that wind direction might affect the ground surface roughness based on nearby infrastructure (or trees, buildings) that interrupt the flow of the wind. For typical bridges, the difference in wind pressure was not significant in selecting the wind exposure category. Therefore, determining the exposure category with the wind direction being perpendicular to the bridge was found to be sufficient as per AASHTO C3.8.1.1.3.

Section 2.3: Wind Pressure Equation

A new wind pressure equation (*Pz*) was provided in the *AASHTO* 8th Ed. specifications (Eqn. 3.8.1.2.1-1), which was defined (in part) as the product of the 3-second gust wind speed (*V*), the pressure exposure and elevation coefficient (*Kz*), gust effect factor (G), and drag coefficient

(C_D). In accordance with the wind pressure equation, the product of the four terms noted above were also multiplied by $2.56x10^{-6}$, where this coefficient was equal to the product of 0.5 multiplied by the density of air and the conversion factors to convert the units of wind speed from mph to fps (Wassef & Ragget, 2014).

Terms in the wind pressure equation were defined to vary across the applicable load combinations: Strength V and Service I limit states were based on constant wind speed, thus, the Kz value for these two load combinations was listed as 1.0. In turn, the elevation coefficient (Kz) was defined to vary at different elevations and for different wind exposure categories as per Table C3.8.1.2.1-1 of *AASHTO*. However, there were no reductions in Kz for structures possessing heights less than 33 ft since the proximity to the ground surface was assumed to prevent the wind pressure to not be accurately calculated due to turbulence.

Section 2.4: Drag Coefficient

To be able to calculate the wind load on a bridge, it is necessary to know the drag coefficient for superstructure components such as the girder type (e.g., I-girder, box-girder) as well as that of other bridge components. The C_D table 3.8.1.2.1-2 in *AASHTO* generalized the coefficient values for many bridge components including I-girder, box-girder, sound barriers, and bridge substructures. The study considered when developing the *AASHTO* 8th Ed. wind provisions (Wassef & Ragget, 2014) also suggested adding wind provisions for wind pressures on superstructures and substructures during construction (and preceding deck construction), with use of unique drag coefficients depending on the superstructure type. Drag coefficients applicable to the construction stages (and for different girder types) were developed as part of recent research (Consolazio & Gurley, 2013). Even though these coefficients were not included in the *AASHTO* 8th Ed. wind provisions, engineers should be aware of the effects the change in drag coefficients can cause during construction, and such considerations may be necessary to implement in FB-MultiPier as part of future efforts.

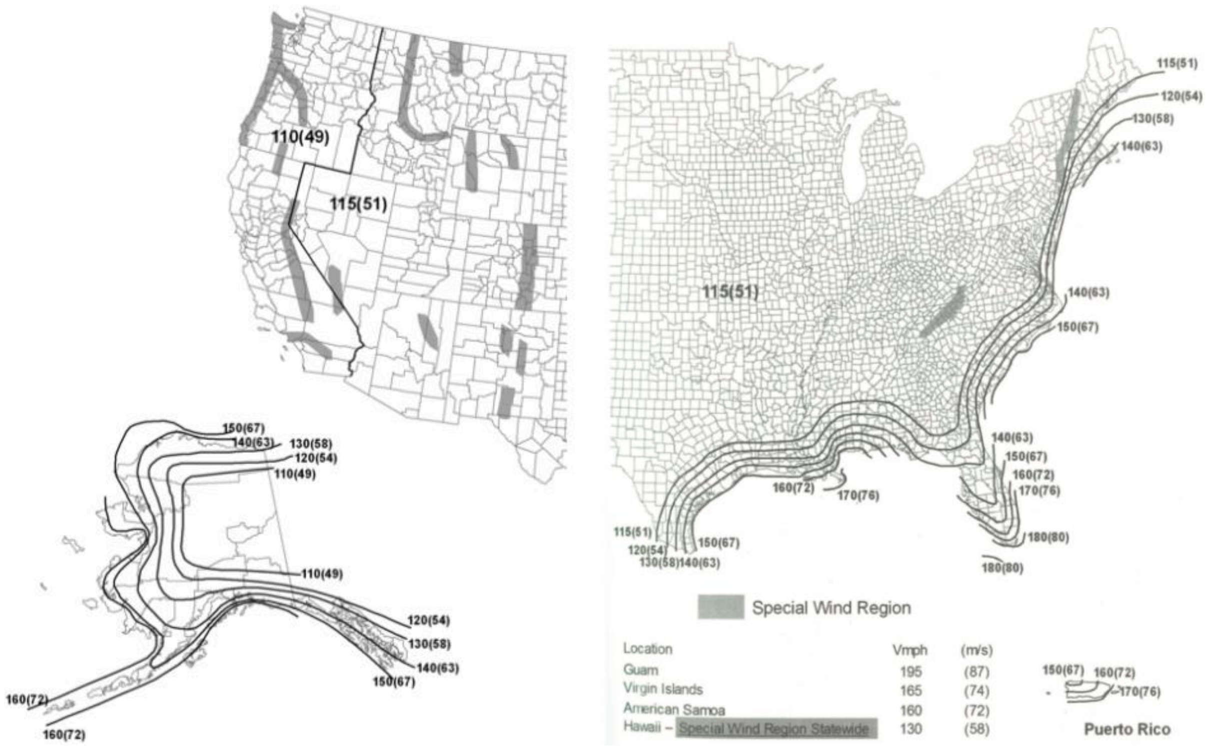


Figure 1 Design Wind Speed, V, in mph (m/s) *(AASHTO, 2017)*

Section 3: Current Wind Load Generator Feature Set in FB-MultiPier

The most currently available version of FB-MultiPier (version 5.4) was not fitted with up-to-date wind pressure calculations for superstructures, substructures, and live load. Documented below are the most currently available components of the Wind Load Generator feature set in FB-MultiPier. In Sec. 4 of this report, the modified and new dialogs to calculate the wind pressures will be presented.

Currently, in order for the *AASHTO* combinations to be made use of in FB-MultiPier bridge models, the intention of making use of design specifications in the model must first be indicated. This is done by navigating to the Analysis Settings page (within the Design Specification Options panel), and checking the “Auto-generation of Load Combinations” checkbox. Once that selection is made, the *AASHTO* page will be enabled (see **Figure *2***). From within this page, *AASHTO* load combinations of interest can be defined, and load types making up each load combination can be defined by entering the “Load Case Manager” dialog.

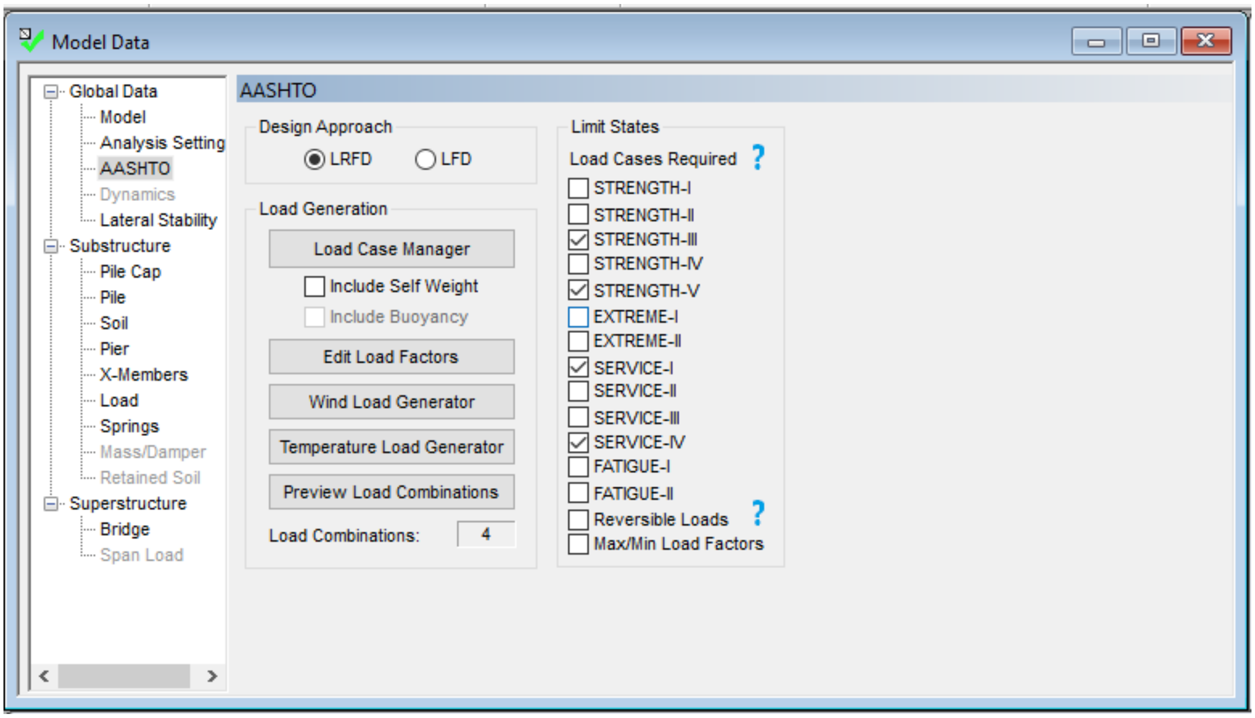


Figure 2 AASHTO Page in FB-MultiPier v5.4

Once the "Load Case Manager" (see **Figure *3***) dialog is accessed, then the litany of AASHTO (LRFD) load types can be included/excluded in the bridge model. Of greatest relevance in the current study are load types (directly or indirectly) associated with wind effects: "Live Load", "Impact", "Wind on Live Load", and "Wind on Structure". These load types must be defined as load cases on the load case manager so that the desired limit states (e.g., Strength II, Strength V, Service I, and Service IV) can then be considered in the form of load combinations. The available types of load cases are based off of Section 3.4 of the *AASHTO* provisions (AASHTO, 2017).

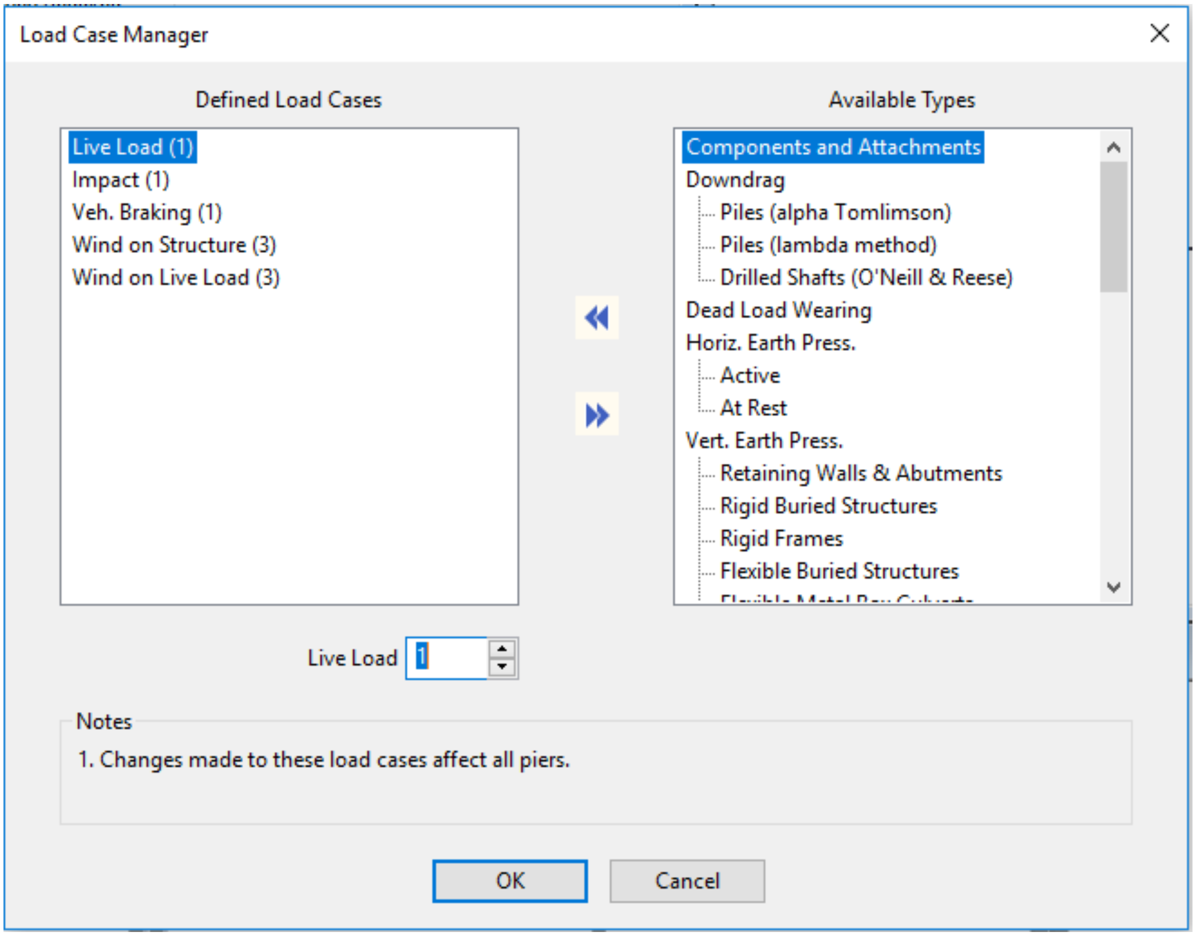
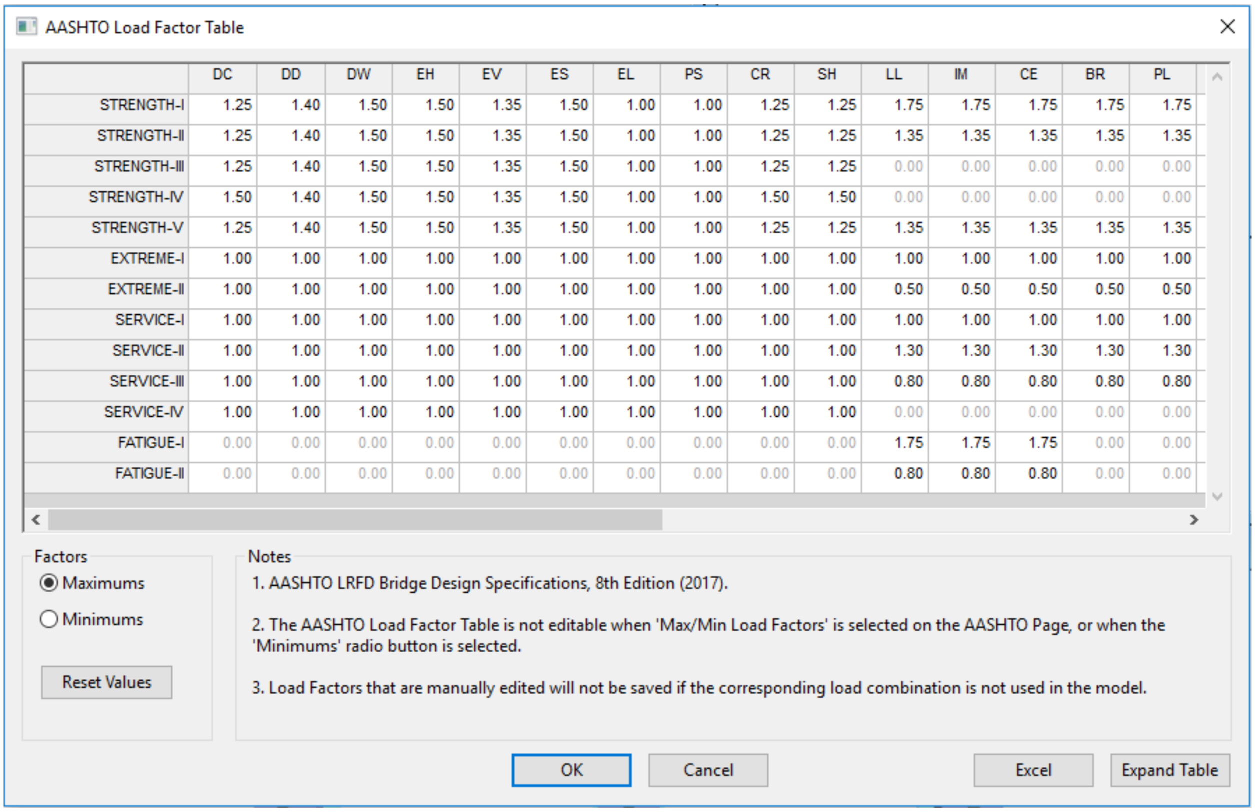


Figure 3 Load Case Manager Dialog in FB-MultiPier v5.4

After the required load types have been added to the model loading regime, then load combinations such as Strength III, Strength V, Service I, and Service IV can subsequently be selected for generating load combinations. At this point, the load factors assigned to each load type within each load combination considered will become editable. These factors can be edited on the "Edit Load Factors" dialog (see **Figure** *4*). Also, these factors (as presented in the program) have been updated to match the load factors listed in the *AASHTO* 8th Ed., Table 3.4.1.1 (AASHTO, 2017).



	DC	DD	DW	EH	EV	ES	EL	PS	CR	SH	LL	IM	CE	BR	PL
STRENGTH-I	1.25	1.40	1.50	1.50	1.35	1.50	1.00	1.00	1.25	1.25	1.75	1.75	1.75	1.75	1.75
STRENGTH-II	1.25	1.40	1.50	1.50	1.35	1.50	1.00	1.00	1.25	1.25	1.35	1.35	1.35	1.35	1.35
STRENGTH-III	1.25	1.40	1.50	1.50	1.35	1.50	1.00	1.00	1.25	1.25	0.00	0.00	0.00	0.00	0.00
STRENGTH-IV	1.50	1.40	1.50	1.50	1.35	1.50	1.00	1.00	1.50	1.50	0.00	0.00	0.00	0.00	0.00
STRENGTH-V	1.25	1.40	1.50	1.50	1.35	1.50	1.00	1.00	1.25	1.25	1.35	1.35	1.35	1.35	1.35
EXTREME-I	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
EXTREME-II	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50
SERVICE-I	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SERVICE-II	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.30	1.30	1.30	1.30	1.30
SERVICE-III	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.80	0.80	0.80
SERVICE-IV	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00
FATIGUE-I	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.75	1.75	1.75	0.00	0.00
FATIGUE-II	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.80	0.80	0.00	0.00

Figure 4 Edit Load Factors dialog in FB-MultiPier v5.4

After the load types and load combinations are defined, the “Bridge Wind Load Generation” dialog can be opened by selecting the “Wind Load Generator” button. As shown in **Figure 5**, this dialog allows the engineer to select one or more angles, ranging from 0 to 75 degrees in 15-degree increments. Also, load instances (up to 25) can be selected to generate a wider variety of loads deriving from wind pressures. In FB-MultiPier v5.4, the wind pressures used in computing wind-induced loads are based on the 6th Ed. of the *AASTHO* wind provisions. Alternatively stated, the wind pressures derive from the base wind pressures that correspond to the fastest-mile measure of wind speed used by the National Weather Service (AASHTO, 2012). The base wind speed was 100 mph and the base wind pressure is 40 or 50 psf, depending on the structural component. Only the superstructure and live load wind pressures are displayed on the Wind Load Generator dialog, leaving the engineer to input the wind loads on the substructure manually.

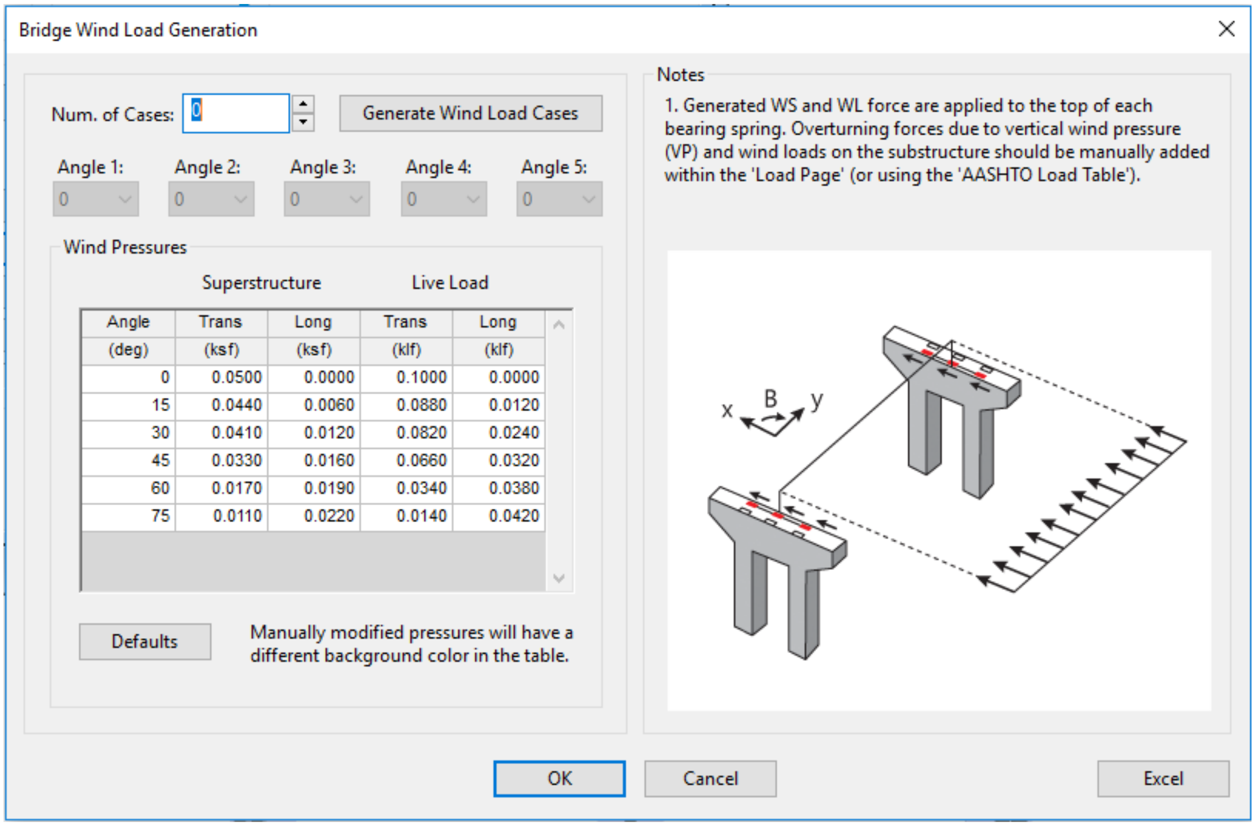


Figure 5 Bridge Wind Load Generation dialog in FB-MultiPier v5.4

Section 4: Proposed Enhancements to the Wind Load Generator Feature Set in FB-MultiPier

Based on recent modifications to the *AASHTO* wind load provisions (recall Sec. 2), and incompatibilities identified in the currently available Wind Load Generator feature set in FB-MultiPier v5.4, the following UI changes are proposed. While the proposed enhancements to the Wind Load Generator in FB-MultiPier are intended to reconcile the as-identified program incompatibilities, it is assumed that engineers making use of the feature set are familiar with the current wind load provisions documented in Sec. 3.8 of the *AASHTO* specifications.

To begin the process of Wind Load Generation, the same first steps detailed in Sec. 3 must be carried out: the “Auto-generation of Load Combinations” checkbox must be set to checked on the program Analysis Settings page, and the *AASHTO* page must be enabled. Once enabled, the *AASHTO* page must be selected to be able to access and perform modeling activities such as defining load types, defining load combinations, (as needed) editing load factors, and generating wind loads (recall **Figure *2***).

Templates for enhanced and new program dialogs were created to (when implemented in FB-MultiPier) intuitively guide the engineer through the process of generating wind loads based on the *AASHTO* wind provisions. The first change seen is a new button labeled “Pair Wind Loads with Limit States” (see **Figure *6***). This new feature is utilized after the engineer has selected the load cases required for the limit states previously discussed in Sec. 3 of this report. The engineer must pair loads with the specified limit state so that, after wind loads are generated, those loads are assigned to the appropriate load combinations.

In the *AASHTO* provisions, there are two types of loads directly associated with wind effects: Wind on Structure (WS) and Wind on Live Load (WL). There are 25 maximum possible load instances (i.e., variations on a standard load type) that can be generated, and this dialog allows the user to pair a given load instance with the desired load combination (see **Figure** *7*). The *AASHTO* provisions state that, for the Strength III and Service I load combinations, the associated load factors for the WS and WL load types are of magnitude 1.0. The WL load type is not applicable to the Strength III and Service IV load combinations, and again, the WS type is of magnitude 1.0. Even so, the program retains the ability for the engineer to manually edit load factors for all load types (and load instances) by opening the "Edit Load Factors" dialog.

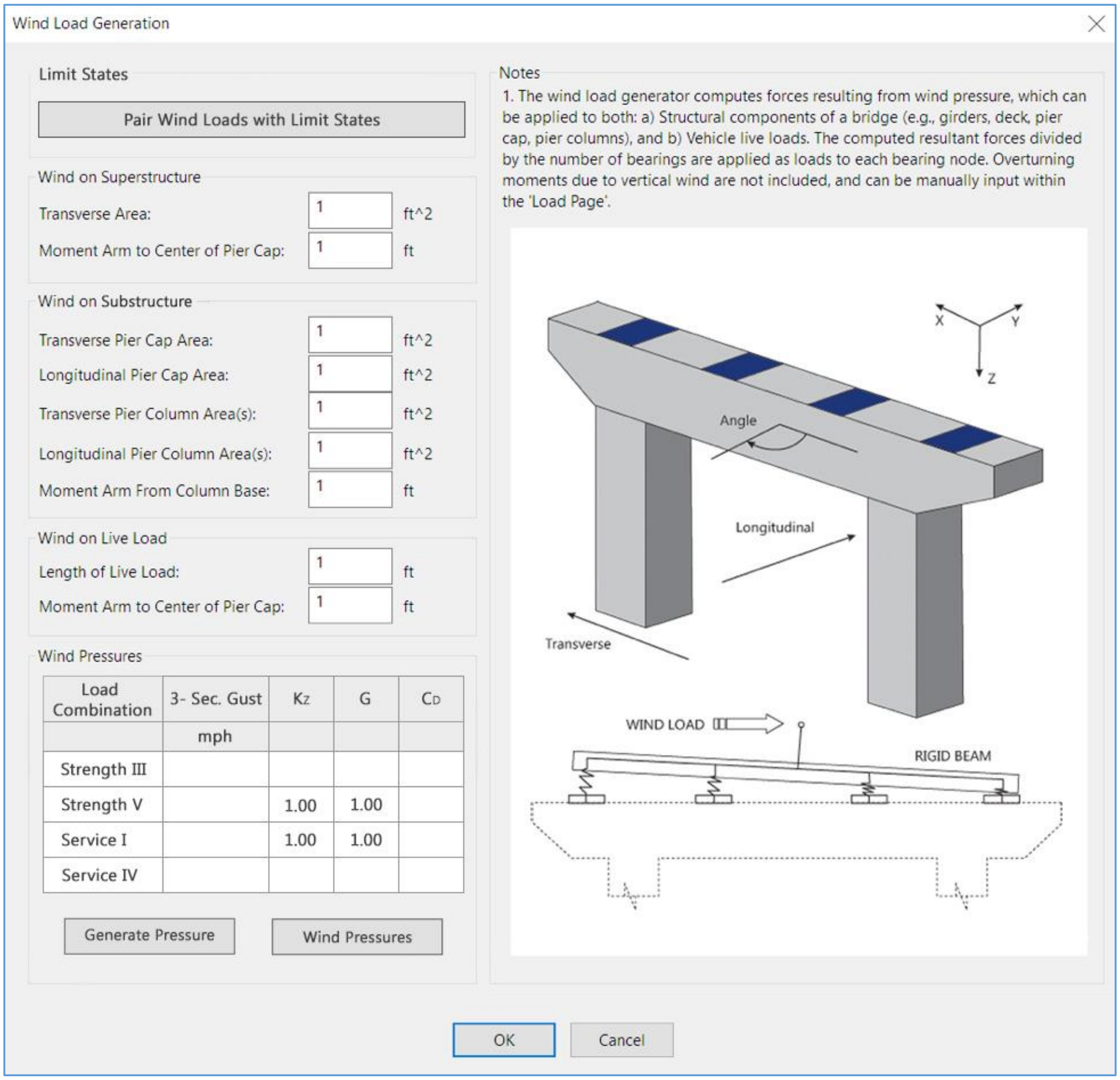


Figure 6 Enhanced Wind Load Generator dialog

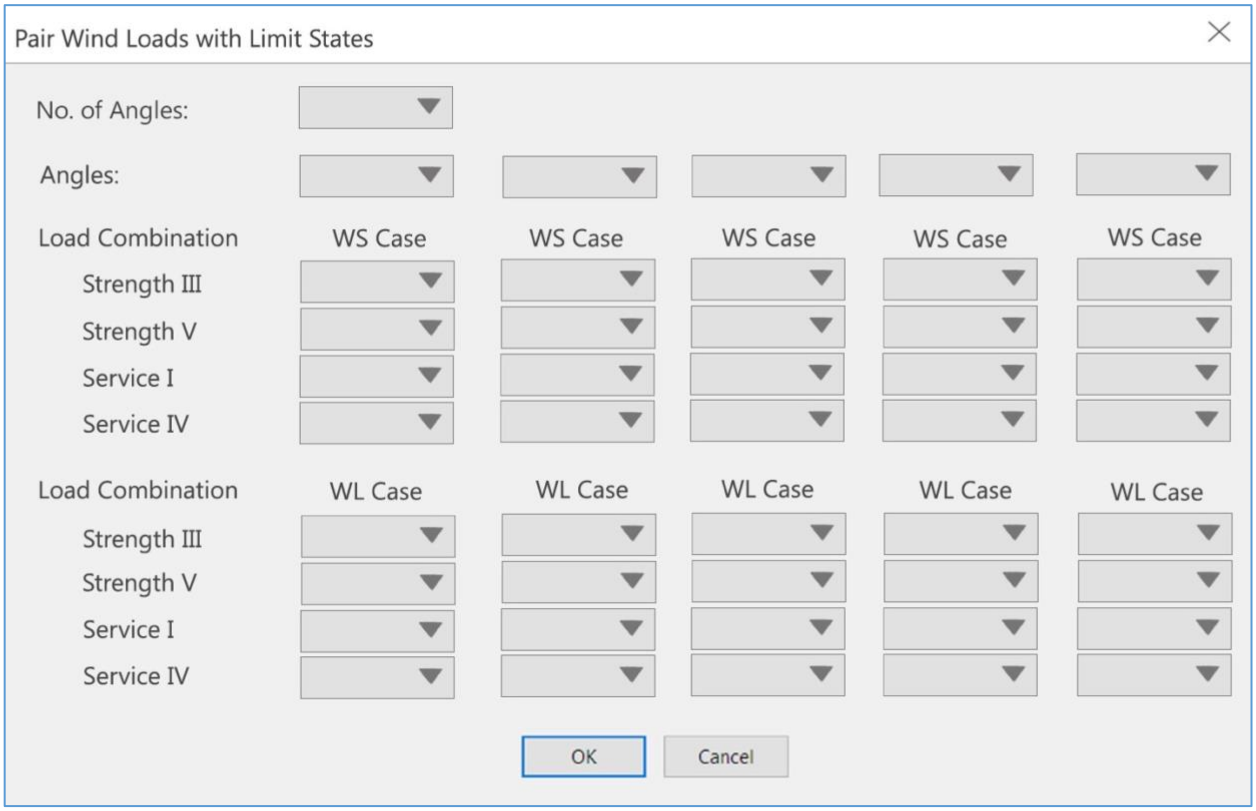
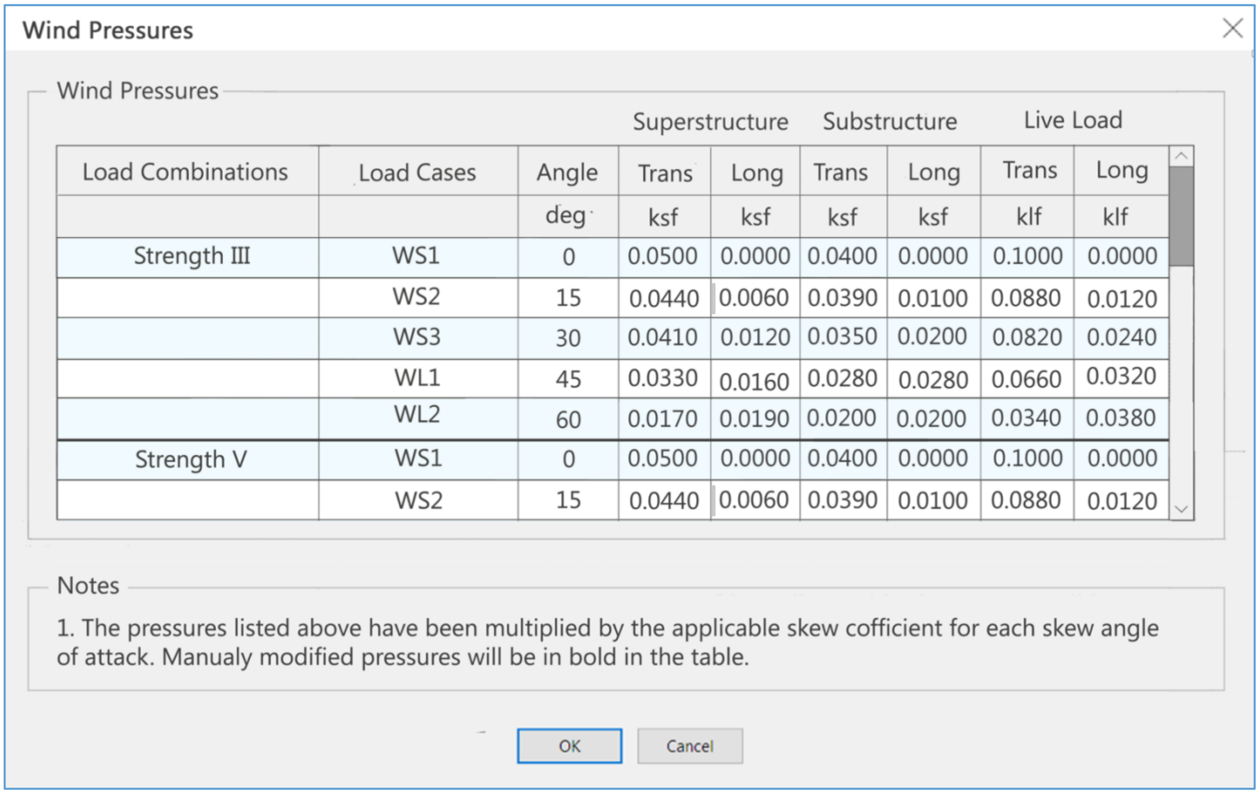


Figure 7 New dialog to Pair Wind Loads with Limit States

Once the wind loads are paired to the desired limit states then wind pressure equation parameters such as C_D, K_z, G, and V can be input, from which the program will automatically calculate the wind pressures. Refer to **Figure *6*** for where the wind pressure information must be input. After all of the variables have been quantified in the table for the respective limit states, then the new "Generate Wind Pressures" button can be clicked to generate the wind pressures (see **Figure *6***). It is worth emphasizing that, upon implementation of these proposed changes, the program automatically calculates wind pressures, which are (in turn) used to compute wind loads on the bridge superstructure and substructure. The wind loads generated will then become visible under the "Loads" page (recall the tree menu in **Figure *2***).

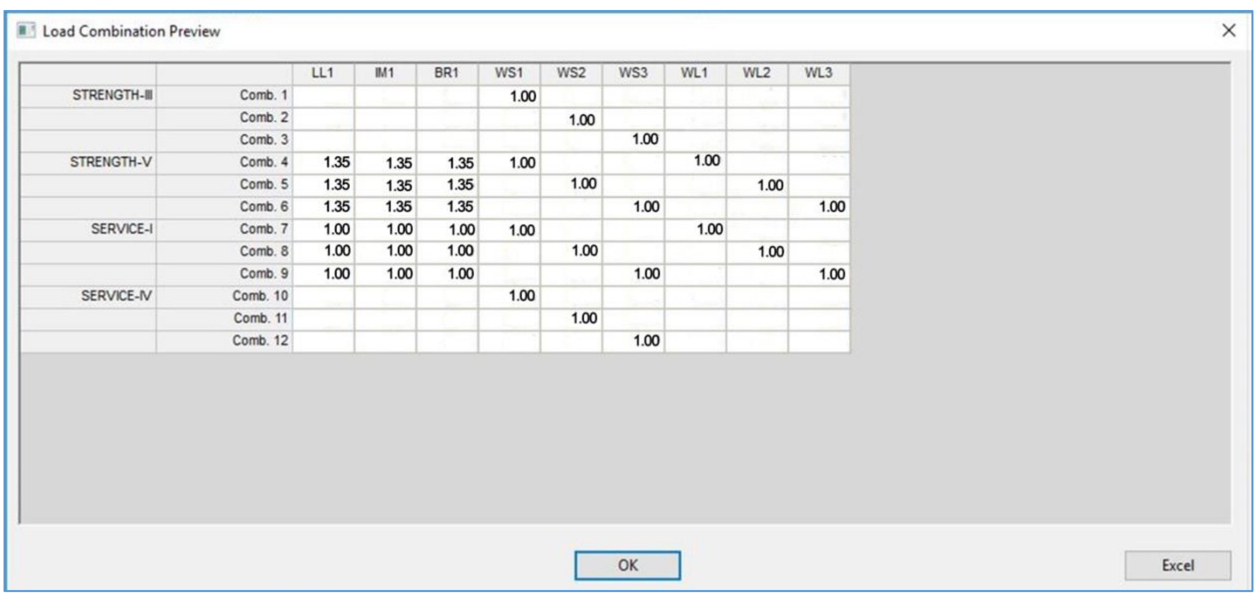
The calculated wind pressures can be reviewed by selecting the "Wind Pressures" button (see **Figure *6***). Once selected, a new dialog will open which tabulates the superstructure, substructure, and live load wind pressures per load combination, load type, and angle (see **Figure *8***). The wind provision that included skew coefficients for the superstructures as explained in Sec. 2 of this report will have been already applied to the tabulated substructure wind pressures.



Load Combinations	Load Cases	Angle	Trans	Long	Trans	Long	Trans	Long
		deg	ksf	ksf	ksf	ksf	klf	klf
Strength III	WS1	0	0.0500	0.0000	0.0400	0.0000	0.1000	0.0000
	WS2	15	0.0440	0.0060	0.0390	0.0100	0.0880	0.0120
	WS3	30	0.0410	0.0120	0.0350	0.0200	0.0820	0.0240
	WL1	45	0.0330	0.0160	0.0280	0.0280	0.0660	0.0320
	WL2	60	0.0170	0.0190	0.0200	0.0200	0.0340	0.0380
Strength V	WS1	0	0.0500	0.0000	0.0400	0.0000	0.1000	0.0000
	WS2	15	0.0440	0.0060	0.0390	0.0100	0.0880	0.0120

Figure 8 New Wind Pressures dialog

A proposed enhancement to the "Load Combination Preview" dialog was also identified, where the load factors that are applied to the load type are assigned the bold attribute for visual emphasis, and cells associated with non-applicable load factors remain blank (see **Figure *9***). In contrast, in the respective feature in the current version of FB-MultiPier (v5.4), values of "0.00" are displayed in cells that are not applicable to a given load combination.



		LL1	IM1	BR1	WS1	WS2	WS3	WL1	WL2	WL3
STRENGTH-III	Comb. 1				1.00					
	Comb. 2					1.00				
	Comb. 3						1.00			
STRENGTH-V	Comb. 4	1.35	1.35	1.35	1.00			1.00		
	Comb. 5	1.35	1.35	1.35		1.00			1.00	
	Comb. 6	1.35	1.35	1.35			1.00			1.00
SERVICE-I	Comb. 7	1.00	1.00	1.00	1.00			1.00		
	Comb. 8	1.00	1.00	1.00		1.00			1.00	
	Comb. 9	1.00	1.00	1.00			1.00			1.00
SERVICE-IV	Comb. 10				1.00					
	Comb. 11					1.00				
	Comb. 12						1.00			

Figure 9 Enhanced Load Combination Preview dialog

Section 5: Case Study

A case study was conducted to illustrate application of the *AASHTO* 8th Ed. wind provisions and to provide a programmatic engineering-calculation resource for developers of the FB-MultiPier software. In this case study, every step was detailed to facilitate guidance for needed changes to engineering calculations (as will be brought about when implementing the proposed UI enhancements). However, it should be noted that only a subset of those values presented in the case study are directly input in the dialogs of the proposed FB-MultiPier Wind Load Generator. Specifically, only the wind speed, gust effect factor, pressure exposure coefficient, and drag coefficient are necessary to be input in the software UI (see **Figure *6***). All engineering calculations cataloged as part of the case study can be found in Appendix A of this report.

For this study, a 33-ft-high girder bridge with span lengths of 100 ft was selected for the calculation of wind loads in accordance with the AASHTO 8th Ed. provisions. The pier and pier cap dimensions were defined as 36 in x 36 in x 33 ft and 36 in x 36 in, respectively. The pier column spacing was 12 ft wide and the pier cap overhang was taken as 7.5 ft on both sides.

The first steps in the calculation procedure involve knowing where exactly the bridge is located since that is what dictates the wind speeds that are going to be used (as well as the wind exposure category). For the case study, South Florida was selected. The 3-second gust wind speed can be taken from Figure 3.8.1.1.2-1 of the *AASHTO* 8th Ed. provisions because it meets all the criteria explained in Sec. 2 of this report. Based on this location, the ground surface roughness category can be chosen, and the applicable wind exposure category selected. Note that the wind exposure category dictates which *Kz* equation to use when evaluating the wind pressure equation. Given the selected location and assumptions for the case study, wind exposure category C was applicable.

After the appropriate wind exposure category is identified and the bridge height is known, the *Kz* equation, which in this case is the *AASHTO Kz(C*) equation 3.8.1.2.1-3, can be solved and the engineer can supply that value as input on the Wind Load Generator dialog (see **Figure *6***). The engineer can also select the gust effect factor and drag coefficient based on the tables provided in Section 3.8 of the *AASHTO* provisions, and further, input these values into the Wind Load Generator.

After the table is populated, the wind pressures can be generated (the generation of which will be automated in the program). In this case study, the substructure and superstructure wind pressures are manually calculated to show the process of converting them into distributed loads, which takes into consideration the depth of the bridge. The Wind on Live Loads are generalized and can be found in Table 3.8.1.3.1 of the *AASHTO* provisions. If the wind loads are skewed relative to the bridge, there are skew coefficients for every 15-degree increment, up to 60 degrees, and the wind pressures must be factored by the applicable skew coefficient.

The superstructure skew-factored wind pressures (transverse and longitudinal components) was found through trigonometry. For example, the transverse component of 15 degrees is found by multiplying the wind pressures by the cosine of 15 degrees, and the longitudinal component was found by multiplying the wind pressures by the sine of 15 degrees. The tabulated results are presented at the end of the case study (see **Figure *10***) exemplify tabulated content that would be displayed on the "Wind Pressures" dialog (see **Figure *8***). While the program will automatically calculate distributed loads associated with these pressures, the manual procedure involves scaling the wind pressures by the skew coefficients, and then integrating over the respective areas.

Conclusions

The wind load provisions contained in current *AASHTO* design specifications allow for bridge designs to be produced that are increasingly economical and resilient. Enhancing design-oriented bridge finite element analysis software to be up-to-date based on governing design specifications is crucial in facilitating effective design of bridges to withstand wind loads. Upon implementation of the newly developed wind load generation process and resources proposed herein, the design-oriented bridge analysis software FB-MultiPier will become equipped with features that align with the current wind provisions. Further, the proposed resources are intended to enable engineers to create more accurate, efficient, and cost-effective bridges by not over- or under-designing bridges to resist wind load effects.

Major aspects of the current work included identifying, formulating, and creating resources for an enhanced wind load generation feature set in FB-MultiPier. The proposed feature set included the effects of different wind speeds, load factors, drag coefficients, gust factors, exposure, and elevation coefficients, and the newly developed (and enhanced) program dialogs were crafted to ensure an intuitive path of execution in supplying these parameters to applicable bridge models. The proposed feature set was also formulated to allow engineers the freedom of pairing a wide variety of wind load variations to a given limit state of interest. Further, the proposed enhancements include automatic calculation of wind loads subsequent to calculation of the wind pressures acting on a given bridge. As outcomes of this effort, and upon implementation of the proposed feature set, the wind pressure calculations in FB-MultiPier will be more accurate in creating wind loads acting on superstructure and substructure portions of bridge models. Implementing these new additions and modifications to the wind load generation process will improve the quality and relevancy of FB-MultiPier. Implementation will also increase the chances that final bridge designs adhere to current design provisions, and thereby, better uphold the safety of the general public.

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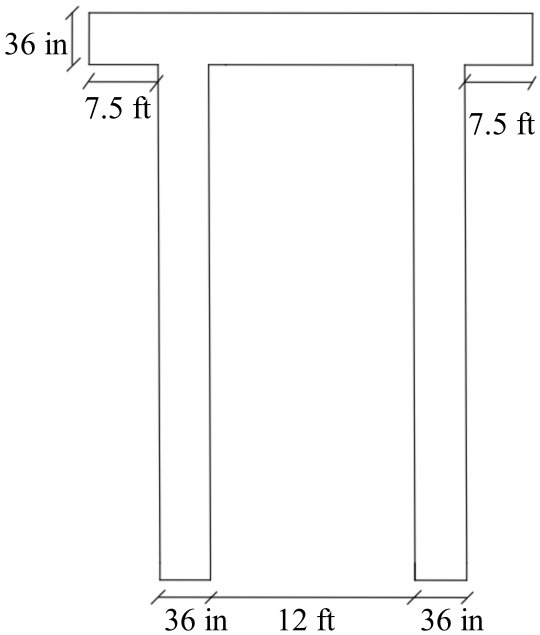
Appendix A Case Study

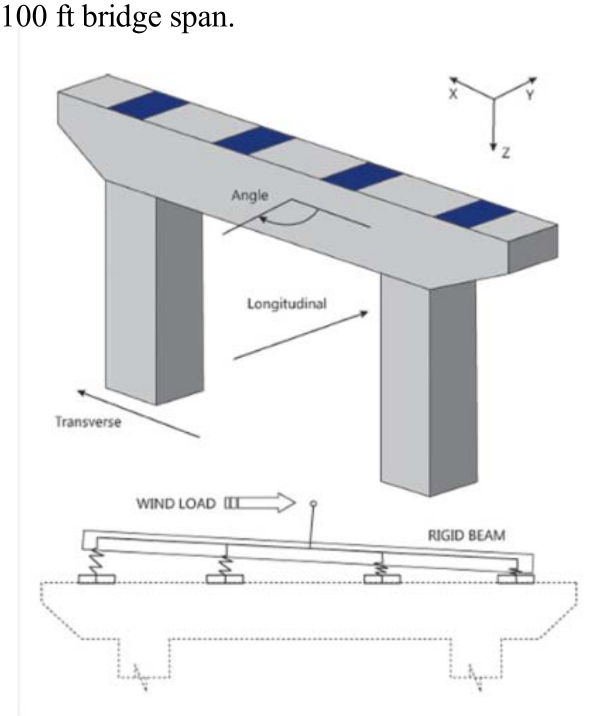
Contained in this appendix is a listing of the programmatic calculations of wind load generation, as developed in Mathcad, and in accordance with the AASHTO 8th Ed. design specifications.

Case Study: AASHTO Wind Loads for Hypothetical Substructure in South Florida

<u>Compute Wind Pressures that Contribute to Strength III, Strength IV, Service I, Service IV Load Combinations</u>

Given: Beam and girder bridge 33 ft high, Pier dimensions are 36 in x 36 in x 33 ft, Pier Cap dimensions are 36 in x 36 in, 12 ft Pier spacing. 100 ft bridge span.





The engineer will refer to section 3.8- Wind Load: WL and WS when using the FB-MultiPier Wind Load Generator.

<u>Exposure Conditions (3.8.1.1.1)</u>

1. Ground Surface Roughness Categories (3.8.1.14)

"Ground surface Roughness C: Open terrain with scattered obstructions having height generally less than 33ft, including flat open country and grasslands..."

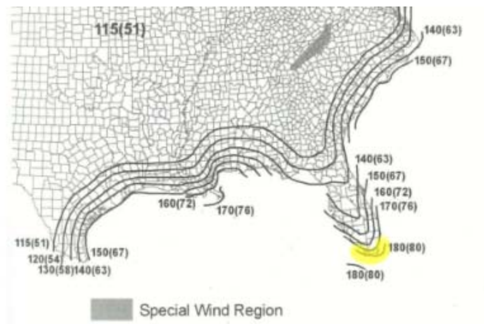
2. Wind Exposure Categories (3.8.1.1.5)

"Wind Exposure Category C: Wind exposure Category shall apply for all cases where Wind Exposure Categories B or D do not apply."

3- sec Gust Wind Speed- V (Refer to table 3.8.1.1.2-1)

Table 3.8.1.1.2-1—Design 3-Second Gust Wind Speed for Different Load Combinations, *V*

Load Combination	3-Second Gust Wind Speed (mph), *V*
Strength III	Wind speed taken from Figure 3.8.1.1.2-1
Strength V	80
Service I	70
Service IV	0.75 of the speed used for the Strength III limit state



Wind Region is in South Florida

$V_{St3} = 180$ mph (Strength III Wind Speed mph - Refer to Figure 3.8.1.1.2-1)

$V_{St5} = 80$ mph (Strength V Wind Speed mph - Refer to Table 3.8.1.1.2-1)

$V_{Se1} = 70$ mph (Service I Wind Speed mph - Refer to Table 3.8.1.1.2-1)

$V_{Se4} = V_{St3} \cdot 0.75 = 135$ mph (Service IV Wind Speed mph - Refer to Table 3.8.1.1.2-1)

Wind Load on Structure: WS (3.8.1.2)

$Z = 33$ ft (Structure height)

$P_z = 2.56 \cdot 10^{-6} \cdot V^2 \cdot K_z \cdot G_e \cdot C_d$ (Wind pressure Eq. 3.8.1.2.1-1)

$$K_{zC} = \frac{\left(2.5 \ln\left(\frac{Z}{0.9834}\right) + 7.35\right)^2}{478.4}$$

(Pressure exposure coefficient for Strength III and Service IV load combinations based on wind exposure category. Eq. 3.8.1.2.1-2)

$K_{zC} = 0.544$

(C3.8.1.2.1- Strength V and Service I load combinations are based on constant wind stopped so Kz is taken as 1.)

$K_z = 1$

$G_e = 1$ (Gust Effect Factor -Table 3.8.1.2.1-1)

Table 3.8.1.2.1-1—Gust Effect Factor, *G*

Structure Type	Gust Effect Factor, *G*
Sound Barriers	0.85
All other structures	1.00

$C_{D\_substructure} = 1.6$ (Drag coefficient - Table 3.8.1.2.1-2: Bridge Superstructure)

$C_{D\_superstructure} = 1.3$ (Drag coefficient - Table 3.8.1.2.1-2: Bridge Substructure)

Table 3.8.1.2.1-2—Drag Coefficient, C_D

Component		Drag Coefficient, C_D Windward	Drag Coefficient, C_D Leeward
I-Girder and Box-Girder Bridge Superstructures		1.3	N/A
Trusses, Columns, and Arches	Sharp-Edged Member	2.0	1.0
	Round Member	1.0	0.5
Bridge Substructure		1.6	N/A
Sound Barriers		1.2	N/A

Wind Load on Live Load: WL (3.8.1.3)

Table 3.8.1.3-1—Wind Load Components on Live Load

Skew Angle (degrees)	Transverse Component (klf)	Longitudinal Component (klf)
0	0.100	0.000
15	0.088	0.012
30	0.082	0.024
45	0.066	0.032
60	0.034	0.038

For the usual girder and slab bridges having an individual span length of not more than 150 ft and a maximum height of 33.0 ft above low ground or water level, the following wind load components on live load may be used:

- 0.10 klf, transverse
- 0.04 klf, longitudinal

Both forces shall be applied simultaneously.

Wind Pressures

Superstructure Wind Pressures

Strength III wind pressure at 0 degree angle

$$P_{z3\_super} = 2.56 \cdot 10^{-6} \cdot V_{St3}^{2} \cdot K_{zC} \cdot G_e \cdot C_{D\_superstructure} \cdot ksf$$

$$P_{z3\_super} = 0.0587 \cdot ksf$$

Strength V wind pressure at 0 degree angle

$$P_{z5\_super} = 2.56 \cdot 10^{-6} \cdot V_{St5}^{2} \cdot K_z \cdot G_e \cdot C_{D\_superstructure} \cdot ksf$$

$$P_{z5\_super} = 0.0213 \cdot ksf$$

Service I wind pressure at 0 degree angle

$$P_{z1\_super} = 2.56 \cdot 10^{-6} \cdot V_{Se1}^{2} \cdot K_z \cdot G_e \cdot C_{D\_superstructure} \cdot ksf$$

$$P_{z1\_super} = 0.0163 \cdot ksf$$

Service IV wind pressure at 0 degree angle

$$P_{z4\_super} = 2.56 \cdot 10^{-6} \cdot V_{Se4}^{2} \cdot K_{zC} \cdot G_e \cdot C_{D\_superstructure} \cdot ksf$$

$$P_{z4\_super} = 0.033 \cdot ksf$$

Substructure Wind Pressures

Strength III wind pressure at 0 degree angle)

$$P_{z3\_sub} = 2.56 \cdot 10^{-6} \cdot V_{St3}^{2} \cdot K_{zC} \cdot G_e \cdot C_{D\_substructure} \cdot ksf$$

$$P_{z3\_sub} = 0.0722 \cdot ksf$$

Strength V wind pressure at 0 degree angle

$$P_{z5\_sub} = 2.56 \cdot 10^{-6} \cdot V_{St5}^{2} \cdot K_{z} \cdot G_{e} \cdot C_{D\_substructure} \cdot ksf \qquad P_{z5\_sub} = 0.0262 \cdot ksf$$

Service I wind pressure at 0 degree angle

$$P_{z1\_sub} = 2.56 \cdot 10^{-6} \cdot V_{Se1}^{2} \cdot K_{z} \cdot G_{e} \cdot C_{D\_substructure} \cdot ksf \qquad P_{z1\_sub} = 0.0201 \cdot ksf$$

Service IV wind pressure at 0 degree angle

$$P_{z4\_sub} = 2.56 \cdot 10^{-6} \cdot V_{Se4}^{2} \cdot K_{zC} \cdot G_{e} \cdot C_{D\_substructure} \cdot ksf \qquad P_{z4\_sub} = 0.0406 \cdot ksf$$

Wind Loads

$D = 10ft$ (Superstructure depth) $\qquad A_{super} = D \cdot 100ft = 1000\,ft^{2}$

Strength III

$$WS1_{St3} = P_{z3\_super} \cdot A_{super} = 58.6643 \cdot kip$$

Strength V

$$WS1_{St5} = P_{z5\_super} \cdot A_{super} = 21.2992 \cdot kip$$

Service I

$$WS1_{Se1} = P_{z1\_super} \cdot A_{super} = 16.3072 \cdot kip$$

Service IV

$$WS1_{Se4} = P_{z4\_super} \cdot A_{super} = 32.9987\,ft \cdot \frac{kip}{ft}$$

$$A_{pier} = 36in \cdot 33ft = 99\,ft^{2}$$

Strength III

$$WS1_{St3} = P_{z3\_sub} \cdot A_{pier} = 7.148 \cdot kip$$

Strength V

$$WS1_{St5} = P_{z5\_sub} \cdot A_{pier} = 2.5952 \cdot kip$$

Service I

$$WS1_{Se1} = P_{z1\_sub} \cdot A_{pier} = 1.987 \cdot kip$$

Service IV

$$WS1_{Se4} = P_{z4\_sub} \cdot A_{pier} = 4.0208\,ft \cdot \frac{kip}{ft}$$

$$A_{cap\_trans} = 36in \cdot 36in = 9\,ft^2$$

$$A_{cap\_long} = 36in \cdot 33ft = 99\,ft^2$$

Strength III

$$WS1_{St3} = P_{z3\_sub} \cdot A_{cap\_long} = 7.148 \cdot kip$$

$$WS1_{St3} = P_{z3\_sub} \cdot A_{cap\_trans} = 0.6498 \cdot kip$$

Strength V

$$WS1_{St5} = P_{z5\_sub} \cdot A_{cap\_long} = 2.5952 \cdot kip$$

$$WS1_{St5} = P_{z5\_sub} \cdot A_{cap\_trans} = 0.2359 \cdot kip$$

Service I

$$WS1_{Se1} = P_{z1\_sub} \cdot A_{cap\_long} = 1.987 \cdot kip$$

$$WS1_{Se1} = P_{z1\_sub} \cdot A_{cap\_trans} = 0.1806 \cdot kip$$

Service IV

$$WS1_{Se4} = P_{z4\_sub} \cdot A_{cap\_long} = 4.0208 \cdot kip$$

$$WS1_{Se4} = P_{z4\_sub} \cdot A_{cap\_trans} = 0.3655 \cdot kip$$

WL1 (Wind on Live Load) is based on Table 3.8.3.1.8.1 of AASTHO.

In order to find the change in wind pressure due to the skew angle, the product of the skew coefficient and the respective (base) wind pressure must be calculated.

Table 3.8.1.2.3a-1—Skew Coefficients for Various Skew Angles of Attack

	Trusses, Columns, and Arches		Girders	
Skew Angle (degree)	Transverse Skew Coefficient	Longitudinal Skew Coefficient	Transverse Skew Coefficient	Longitudinal Skew Coefficient
0	1.000	0.000	1.000	0.000
15	0.933	0.160	0.880	0.120
30	0.867	0.373	0.820	0.240
45	0.627	0.547	0.660	0.320
60	0.320	0.667	0.340	0.380

Load Combinations	Load Cases		Superstructure		Substructure		Live Load	
		Skew Angle (degrees)	Transverse Component ksf	Longitudinal Component ksf	Transverse Component ksf	Longitudinal Component ksf	Transverse Component klf	Longitudinal Component klf
Strength III	WS1	0	0.0587	0.0000	0.0722	0.0000	0.1000	0.0000
		15	0.0567	0.0311	0.0635	0.0087	0.0880	0.0120
		30	0.0491	0.0600	0.0592	0.0142	0.0820	0.0240
		45	0.0347	0.0849	0.0477	0.0231	0.0660	0.0320
		60	0.0174	0.1039	0.0245	0.0274	0.0340	0.0380
Strength V	WS1	0	0.0213	0.0000	0.0262	0.0000	0.1000	0.0000
	WL1	15	0.0206	0.0311	0.0231	0.0031	0.0880	0.0120
		30	0.0178	0.0600	0.0215	0.0052	0.0820	0.0240
		45	0.0126	0.0849	0.0173	0.0084	0.0660	0.0320
		60	0.0063	0.1039	0.0089	0.0100	0.0340	0.0380
Service I	WS1	0	0.0163	0.0000	0.0201	0.0000	0.1000	0.0000
	WL1	15	0.0157	0.0311	0.0177	0.0024	0.0880	0.0120
		30	0.0136	0.0600	0.0165	0.0040	0.0820	0.0240
		45	0.0096	0.0849	0.0133	0.0064	0.0660	0.0320
		60	0.0048	0.1039	0.0068	0.0076	0.0340	0.0380
Service IV	WS1	0	0.0330	0.0000	0.0406	0.0000	0.1000	0.0000
		15	0.0319	0.0311	0.0357	0.0049	0.0880	0.0120
		30	0.0276	0.0600	0.0333	0.0080	0.0820	0.0240
		45	0.0195	0.0849	0.0268	0.0130	0.0660	0.0320
		60	0.0098	0.1039	0.0138	0.0154	0.0340	0.0380

Figure 10 Wind Pressure Results