CONSIDERATIONS IN WIND DESIGN OF WOOD STRUCTURES

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Proper design of wood structures to resist high wind loads requires the correct use of wind load provisions and member design properties. A thorough understanding of the interaction between wind loads and material properties is important in the design process.

There are varying wind load provisions in local, state and model building codes currently used in the United States. Most of these provisions are based on wind engineering research conducted over the last 50 years. Proposals to change current code provisions are the result of interpretations of new state-of-the-art wind engineering research.

The wind load provisions of the national load standard *ASCE 7-98 Minimum Design Loads for Buildings and Other Structures* include general wind load provisions which, in turn, are used as the basis for wind load requirements in most U.S. building codes. For the purposes of this paper, the references to wind loads in this article have been limited to the provisions found in *ASCE 7-98*.

Wind Load Provisions

Design wind load provisions in *ASCE 7-98* are based on wind speed data collected during severe wind events in the United States. The wind speed contours provided in *ASCE 7-98* are presented in terms of three second gust.   Three second gust wind speed is based on the peak wind speed at a given height and exposure averaged over 3 seconds. The three second gust wind speed data has been statistically adjusted to a 50-year recurrence interval with an average annual probability of occurrence of 2 percent. The data has also been adjusted to a reference height of 33 feet and Exposure Category B, which assumes a flat, open terrain with scattered obstructions.   The wind load provisions of *ASCE 7-98* provide adjustments for variations from reference conditions such as increased wind speeds during hurricane events, different exposure conditions, different elevations, and localized peak gusts.

ASCE 7-98 contains separate provisions for the design of major structural elements using "Main Wind Force-Resisting System" (MWFRS) loads and secondary structural elements using "Component & Cladding" (C&C) loads. In building design, MWFRS loads have been developed to represent critical loads on the main structural elements from the two major orthogonal directions. These loads "envelope" the major structural actions induced on a building from various wind directions and for various building geometries, roof heights and roof slopes.

C&C loads have been developed to represent peak gusts which occur over small areas as a result of localized funneling and turbulence. Localized load increases can approach 300% at corners and ridges under certain configurations and require special considerations when designing for these loads. In wood structures, wind damage surveys have indicated that these localized loads can cause failures of connections in small areas which can effect the overall Main Wind Force Resisting System.

When designing a structural wood member, a decision must be made whether a member is a MWFRS element, a C&C element, or an element of both systems. *ASCE 7-98* defines the MWFRS as an assemblage of major structural elements assigned to provide support and stability for the overall structure. The system generally receives wind loading from more than one surface.   Components and cladding are defined as elements of the building envelope that do not qualify as part of the MWFRS. Components and cladding are either directly loaded by the wind or receive wind loads originating at relatively close locations, and which transfer these loads to the MWFRS. However, some elements such as roof trusses, load-bearing studs, and structural sheathing have been identified in both systems. One suggested interpretation is to design these elements for the MWFRS loads they would receive as part of the MWFRS and, separately, design these elements for the C&C loads they would receive if

they were only a C&C element. In many cases this would require at least two checks; however, differences in the load cases and estimated stresses make it both necessary and beneficial to separately check both cases. Moreover, under certain common conditions, elements can be pre-engineered for C&C loads.

Allowable Design Stresses

Once the induced loads on a wood member or connection have been determined, that element can be designed. Structural wood members and connections should be designed using the appropriate provisions of the local building code. For the design of solid-sawn wood members and general connections, the codes normally reference or include provisions from the *National Design Specification® for Wood Construction (NDS®)*. Included in NDS design provisions are various adjustments to design values. Among these adjustments is the duration of load (C_D) factor.

Wood strength properties have been observed to exhibit increased capacities under shorter durations of maximum load. This phenomenon has been analyzed extensively in the U.S. and in countries around the world. To account for this phenomenon in design, the U.S. Forest Service, Forest Products Laboratory in Madison, Wisconsin developed the "Madison Curve" which relates the maximum load-carrying capacity to a given load duration.

Most wood member design properties and connection capacities in the NDS are based on 10-minute test values which have been reduced for the effects of defects, stress concentrations, safety and duration of load. The duration of load adjustment reduces a 10-minute design value to a 10-year design value by dividing by a factor of 1.6 based on the "Madison Curve". During a severe wind event, maximum peak wind gusts on a structural member or connection have a cumulative duration of approximately 1-10 seconds. Worst case estimates by wind load experts have indicated that over the life of a structure the cumulative duration of these maximum loads would be less than 1 minute. NDS provisions specify an increase of 1.6 which returns the design capacities of the wood members or connections to the 10-minute test duration values.

While a duration of load increase is allowed for most design properties and connections, there are a few important exceptions. For lumber, a duration of load increase is not permitted for compression perpendicular-to-grain ($F_{C\perp}$), and Modulus of Elasticity (E) design values. These properties are based on deformation and stiffness limits, which are not directly affected by the duration of load phenomenon. For panel product systems, published design capacities in the building codes for shear walls and diaphragms are expressed in terms of the test duration and need only be adjusted for long-term loading. In some codes the shear capacity of wood structural panel shearwalls and diaphragms, resisting wind loads, is permitted to be multiplied by a factor of 1.4 . In addition, information on proprietary products and systems should be reviewed to determine if C_D adjustments of design capacities are permitted for those products.

Design Example

A 36'x60' one-story wood-frame building is to be built on a site located in a 120 mph three second gust wind zone and on terrain representative of Exposure B. The walls will be constructed using 10-foot studs spaced 16 inches on center. The roof will be constructed using trusses spanning 36 feet spaced 24 inches on center and having 2 foot eave overhangs. The mean roof height will be approximately 15 feet and the roof angle will be approximately 20 degrees. The base velocity pressure can be calculated using the following equation:

$$q_h = 0.00256 K_z K_{zt} K_d V^2 I$$
$$= 21.93 \text{ psf}$$

Where:

q_h	=	Velocity pressure evaluated at height, h, above the ground, psf (Exposure B)
K_z	=	Exposure coefficient evaluated at height, h, above the ground (ASCE 7-98 Table 6-5)
	=	0.70 (Exposure B, 15' mean roof height)
K_{zt}	=	Topographic factor (ASCE 7-98 Figure 6-2)
	=	1.0
K_d	=	Wind directionality factor (ASCE 7-98 Table 6-6)
	=	0.85
I	=	Importance factor
	=	1.0 (Category II, ASCE 7-98 Table 6-1)
V	=	Three second gust wind speed, mph
	=	120 mph

Using the calculated base velocity pressure, MWFRS design loads can be determined using the following equation:

$$p_{3\text{-sec gust}} = q_h(GC_{pf}) - q_h(GC_{pi})$$

Where:

$p_{3\text{-sec gust}}$	=	Design wind pressure, psf (MWFRS)
q_h	=	Velocity pressure, psf (120 mph, Exposure B)
	=	21.93 psf
GC_{pf}	=	External pressure coefficient
	=	0.80 (Edge Zone - Windward Wall)
	=	0.53 (Interior Zone - Windward Wall)
	=	-0.64 (Edge Zone - Leeward Wall)
	=	-0.43 (Interior Zone - Leeward Wall)
	=	-0.48 (Edge Zone - Side Walls)
	=	-0.45 (Interior Zone - Side Walls)
	=	-1.07 (Edge Zone - Windward Roof, 20° roof angle)
	=	-0.69 (Interior Zone - Windward Roof)
	=	-0.69 (Edge Zone - Leeward Roof, 20° roof angle)
	=	-0.48 (Interior Zone - Leeward Roof)
GC_{pi}	=	Internal pressure coefficient
	=	0.18 (internal pressurization)
	=	-0.18 (internal suction)
	=	0.68 (underside overhang pressurization)

For C&C design, the "effective" load area of the component must be determined to determine the external pressure coefficients. For rectangular load areas, *ASCE 7-98* allows the area to be calculated as, $A = L^2/3$. For this example, the C&C design loads for studs can be calculated using the following equation and inputs:

$$p_{C\&C} = q_h(GC_p) - q_h(GC_{pi})$$

Where;

$p_{C\&C}$ = Design wind pressure, psf (C&C)

q_h = Velocity pressure, psf (120 mph, Exposure B)
= 21.93psf

GC_p = External pressure coefficient
= 0.91 (windward wall, 33 ft^2)
= -1.22 (leeward wall, 3' edge, 33 ft^2)
= -1.00 (leeward wall, interior, 33 ft^2)

GC_{pi} = Internal pressure coefficient
= 0.18 (internal pressurization)
= -0.18 (internal suction)

Using the equations and values given above, loads for design of the exterior load-bearing studs can be derived. Tabulated below are design loads for the MWFRS and C&C load cases:

	MWFRS Loads	
	Internal Pressurization	Internal Suction
Windward Walls		
Edge Zone	13.59	21.49
Interior Zone	7.68	15.57
Leeward Walls		
Edge Zone	-17.98	-10.09
Interior Zone	-13.38	-5.48
Side Walls		
End Zone	-14.47	-6.58
Interior Zone	-13.82	-5.92
Wind Perpendicular to Ridge		
Windward Roof		
Edge Zone	-27.41	-19.52
Interior Zone	-19.08	-11.18
Windward Roof Overhang		
Edge Zone	-38.38	-38.38
Interior Zone	-30.04	-30.04
Leeward Roof		
Edge Zone	-19.08	-11.18
Interior Zone	-14.47	-6.58
Leeward Roof Overhang		
Edge Zone	-19.08	-11.18
Interior Zone	-14.48	-6.58

	C&C Loads	
	Internal Pressurization	Internal Suction
Windward Walls	16.01	23.90
Leeward Walls (Edge)	-30.70	-22.81
Leeward Walls (Interior)	-25.88	-17.98

After determining the design wind loads on the structure, building components and assemblies can be designed. All pertinent load combinations should be considered. In *ASCE 7-98* the following load combinations should be considered for allowable stress design:

1) Dead
2) Dead + Live$_f$ + Fluid + Earth + Self Straining + (Live$_r$ or Snow or Rain)
3) Dead + Live$_f$ + (Wind or 0.7*Seismic) + (Live$_r$ or Snow or Rain)
4) 0.6*Dead + Wind + Earth
5) 0.6*Dead + 0.7*Seismic + Earth

When structural effects due to two or more loads in combination with dead load, but excluding earthquake load, are investigated in the load combinations of ASCE 7-98, the combined effects due to the two or more loads multiplied by 0.75 plus effects due to dead loads shall not be less than the effects from the load combination of dead load plus the load producing the largest effects.

Under most design conditions, many of these load combinations can be dismissed. For the design of load-bearing studs in the example case, it is assumed that the building will be located in an area that receives little or no snow, that rain can not pond on the roof, and that roof live loads will not be present during a high-wind event. In addition, the studs only support the roof and ceiling loads, therefore, a special case for floor live loads need not be considered. Given these assumptions, only the following load combinations need to be considered in this example:

1) Dead
2) Dead + Live$_f$ + (Wind or 0.7*Seismic) + (Live$_r$ or Snow or Rain)
3) 0.6*Dead + Wind + Earth

For this example, live and dead loads in the structure must be determined. Tabulated below are the assumed roof and ceiling live and dead loads.

	Dead Load	Live Load
Roof	10 psf	20 psf
Ceiling	5 psf	10 psf
Wall	11 psf	---

The duration of load adjustment and induced loads exerted on the studs for each load case and combination are tabulated below. Note that the loads tabulated below are for End Zone pressures, as they represent the worst case design pressure.

| Load Combination | C_D Adjustment | MWFRS | | C&C |
		Axial Load	Lateral Moment	Lateral Moment
1) Dead	0.9	532 lbs. (C)	0 in-lbs.	0 in-lbs.
2) Dead + Live$_r$	1.25	1064 lbs. (C)	0 in-lbs.	0 in-lbs.
3) Dead + Wind	1.6			
Wind Perpendicular to Ridge				
Pressurization				
Windward Studs		-464 lbs. (T)	2711 in-lbs.	3194 in-lbs.
Leeward Studs		-324 lbs. (T)	3587 in-lbs.	6125 in-lbs.
Suction				
Windward Studs		-276 lbs. (T)	4287 in-lbs.	4768 in-lbs.
Leeward Studs		- 113 lbs. (T)	2013 in-lbs.	4551 in-lbs.

The final step in design of the studs is to choose a member which has sufficient design capacity to resist the induced loads tabulated above. Stud walls are a hybrid system in wind engineering terminology. Studs should be designed using MWFRS pressures when considering the combined interactions of axial and bending stresses; and designed using C&C pressures when considering axial or bending stresses individually. This interpretation was developed because only MWFRS pressures provide loads which have been temporally and spatially averaged for different surfaces (MWFRS loads are considered to be time-dependent loads). Since C&C loads attempt to address a "worst case" loading on a particular element during the wind event, these loads are not intended for use when considering the interaction of loads from multiple surfaces (C&C loads are not considered to be time-dependent loads) In the above example, stud design is limited by the C&C load case. This is not uncommon and in most cases can be considered the controlling limit in wind design of loadbearing and non-loadbearing exterior studs. However, until sufficient boundary conditions are placed on this simplification, both MWFRS and C&C load cases should be considered. These assumptions were also used in the development of the *Wood Frame Construction Manual for One- and Two-Family Dwellings, 1995 High Wind Edition* (WFCM-SBC).

For this example, Hem-Fir #2 - 2x4 was chosen. The following tabulated base design values were taken from the NDS Supplement:

F_b = 850 psi
F_t = 525 psi
F_c = 1300 psi
MOE = 1,300,000 psi

Applying the appropriate adjustments and checking each load combination as follows:

1) Dead Loads

$$f_c = C/A$$
$$= 532/5.25 \qquad = \qquad 101 \text{ psi}$$

$$F_c^* = F_c * C_D * C_F$$
$$= 1300*0.9*1.15 \qquad = \qquad 1346 \text{ psi}$$

$$F_c' = F_c^* * C_p$$
$$= 1346*0.233 \qquad = \qquad 314 \text{ psi}$$

$$f_c \qquad\qquad \# \qquad F_c'$$
$$101 \text{ psi} \qquad \# \qquad 314 \text{ psi} \qquad \mathbf{T}$$

2) Dead + Live Loads

$$f_c = 1064/5.25 \qquad = \qquad 203 \text{ psi}$$

$$F_c^* = F_c * C_D * C_F$$
$$= 1300*1.25*1.15 \qquad = \qquad 1869 \text{ psi}$$

$$F_c' = F_c^* * C_p$$
$$= 1869*0.171 \qquad = \qquad 320 \text{ psi}$$

$$f_c \qquad\qquad \# \qquad F_c'$$
$$203 \text{ psi} \qquad \# \qquad 320 \text{ psi} \qquad \mathbf{T}$$

3) Dead + Wind Loads (Wind Perpendicular to Ridge - Windward Studs)

<u>MWFRS Loads</u>

$$f_t = T/A$$
$$= 464/5.25 \qquad = \qquad 88 \text{ psi}$$

$$F_t' = F_t * C_D * C_F$$
$$= 525*1.6*1.5 \qquad = \qquad 1260 \text{ psi}$$

$$f_b = M/S$$
$$= 2711/3.06 \qquad = \qquad 885 \text{ psi}$$

$$F_b^* = F_b * C_D * C_F * C_r$$
$$= 850*1.6*1.5*1.5 \qquad = \qquad 3060 \text{ psi}$$

$$F_b^{**} = F_b * C_D * C_F * C_r$$
$$= 850*1.6*1.5*1.5 \qquad = \qquad 3060 \text{ psi}$$

$$f_t/F_t' + f_b/F_b^* \qquad\qquad \# \qquad 1.0$$
$$88/1260 + 885/3060 = 0.36 \qquad \# \qquad 1.0 \qquad \mathbf{T}$$

$$(f_b - f_t)/F_b^{**} \qquad\qquad \# \qquad 1.0$$
$$(885-88)/3060 = 0.26 \qquad \# \qquad 1.0 \qquad \mathbf{T}$$

<u>C&C Loads</u>

$$f_b = M/S$$
$$= 3194/3.06 \qquad = \qquad 1044 \text{ psi}$$

$$F_b' = F_b * C_D * C_F * C_r$$
$$= 850*1.6*1.5*1.5 \qquad = \qquad 3060 \text{ psi}$$

$$f_b \qquad\qquad \# \qquad F_b'$$
$$1044 \text{ psi} \qquad \# \qquad 3060 \text{ psi} \qquad \mathbf{T}$$

The other cases considered under load combination 3, dead plus wind, can be calculated in a similar manner. Tabulated below are the load/resistance ratios for each load combination and load case.

	MWFRS	C&C
Load Combination	Load/Resistance	Load/Resistance
1) Dead	0.32	---
2) Dead + Live$_r$	0.63	---
3) Dead + Wind		
Wind Perpendicular to Ridge		
Pressurization		
Windward Studs	0.36	0.34
Leeward Studs	0.43	0.65
Suction		
Windward Studs	0.50	0.51
Leeward Studs	0.23	0.49

Summary

Determination of wind loads and material resistance must be considered together. Adjustments of reference wind conditions to extreme-value peak gusts require designers to make similar adjustments to design properties to ensure equivalent and economic designs.

Major structural elements should be designed for MWFRS loads and secondary cladding elements should be designed for C&C loads. Components and assemblies which receive loads both directly and as part of the MWFRS should be checked for MWFRS and C&C loads independently.

In cases where components and assemblies must be designed for lateral wind loads the controlling design case often will be wind acting alone. However, each load combination should be considered thoroughly before being dismissed.

As the wind load provisions in *ASCE 7-98* and the Building Codes continue to change, the wood industry must keep abreast of these changes. Efforts must be made to improve engineering knowledge and procedures to ensure adequate design of structures in high wind areas.

REFERENCES

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