ESWL- Multi-Sector Combination for Wind Loading of Lattice Towers

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ABSTRACT

The Equivalent Static Wind Load (Extended LRC-ESWL) and the Multi-Sector (directionality) methods have both been available for around thirty years. However, this paper describes their first use in combination - for two lattice broadcasting towers with square cross section. The probability distributions of wind speeds for the calculations were based on those in AS/NZS1170.2:2021 converted from gust to mean (10-minute) values. The Standard was also used to assess terrain and topographic effects. Separate predictions were made of bending moments and shear forces, and the accompanying effective wind load distributions with height, for the four wind directions normal to the faces, and for the four oblique directions along the diagonals. The latter case largely governs the design/checking for strength of the legs of a tower with a square cross section, and the former controls the sizing of the bracing members. The results of the calculations by the ESWL and M-S approaches are compared with direct calculations using AS/NZS1170.2. For the examples discussed, significant reductions in the calculated wind-induced bending moments are found.

BACKGROUND

Equivalent Static Wind Load (ESWL) Distributions

Tall structures such as television towers, are governed by wind loading, and will experience some resonant dynamic excitation at design wind speeds, in addition to the static (mean), and quasi-static along-wind loading. Wind loading codes and standards, such as AS/NZS1170.2 (Standards Australia, 2021), inevitably simplify the combined loading distributions to a *single* variation with height. In the case of AS/NZS 1170.2 (Standards Australia, 2021) this is a 'gust envelope loading' distribution, but other methods often use a resonant (inertial) loading distribution, which typically follows the first mode shape of the structure.

The Equivalent Static Wind Load (Extended LRC-ESWL) approach, (abbreviated here simply as 'ESWL'), (Holmes 1996a), separately calculates the distribution of effective wind loads for the mean (fully-correlated) component, the partially correlated gusting ('background') component and the resonant dynamic (inertial) component. Because of the differing effects of correlation, the distribution of effective background loading, based on the load-response-correlation, or 'LRC', approach, varies with the load effect – i.e. with the height, *s*, on the structure of the bending moment, shear force or member force for which the distribution is required. This results in some dependence of the combined equivalent static wind load on the height of the load effect, *s*.

Unlike AS/NZS1170.2, the ESWL method allows for the incorporation of 'aerodynamic' damping (Holmes 1996b) as well as structural damping. The aerodynamic damping component, which is proportional to mean wind speed, is quite significant for structures with relatively low mass, such as lattice towers, and often exceeds the structural damping at design wind speeds.

Multi-Sector Probability

The multi-sector (M-S) method is a simple and accurate method for combining structural responses to wind loading (Holmes 1991, 2020). The multi-sector method was used to combine probabilistically the bending moments and shears from the various wind directions, for the structures discussed in this paper.

The relationship between the return period, $R_{P,a}$, for exceedance of a specified structural response from *all* direction sectors, and the return periods for the same wind speed from direction sectors θ_1, θ_2 etc, is given in Equation (1):

$$\left(1 - \frac{1}{R_{P,a}}\right) = \prod_{i=1}^{N} \left(1 - \frac{1}{R_{P,\theta_i}}\right) \tag{1}$$

In terms of *average recurrence interval* (ARI), $R_{I,a}$,, the equivalent relationship is Equation (2):

$$\frac{1}{R_{I,a}} = \sum_{i=1}^{N} \frac{1}{R_{I,\theta_i}} \tag{2}$$

Equations (1) and (2) follow from the assumption that the wind speeds, and hence structural responses, from each direction sector are statistically independent of each other. This is a good, accurate, assumption for extreme responses at high return periods (RP) or ARIs, as required for ultimate limit states design. For lower values of RP or ARI, it may be slightly conservative, (Holmes 2020).

EXAMPLE STRUCTURES

The ESWL and M-S approaches were applied to two tall steel television towers in southern Australia. Tower 1 is a 140m tall square-plan lattice tower, 15.6m wide at base with a tapered section from ground level to 97.5m. From 97.5m to 127.5m the tower has a constant width of 1.83m; from 129m to 140m, the tower has a constant width of 1.38m. Above 140m, the tower supports a 15m long 4-sided UHF column, giving a total height above ground level of 155 m.

Tower 2 is a taller 164m square-plan lattice tower 'eiffelated' in shape, 24m wide at base with two tapered sections and bend line at about 96m. It supports a 15m long 4-sided, aerodynamically 'solid' UHF antenna, with a tuned liquid damper at its tip, giving a total height above ground level of 178.5m.

On both towers, there are numerous VHF/FM antennas and other mobile phone carrier antennas at lower levels. Both structures are located in relatively complex terrain, requiring adjustment of design wind speeds at each height level for terrain and topography. These adjustments were made using the methods of *Section 4* of AS/NZS 1170.2 and are not discussed here. Drag coefficients for the lattice tower sections and antennas, and aerodynamic interference factors for the ancillaries – antennas, ladders, cable trays etc, were all obtained from *Appendix C* in AS/NZS1170.2:2021.

The calculation of the resonant component of wind loading requires mode shapes and frequency for the first mode of vibration. These were calculated in a structural model using MSTOWER software. The first mode frequencies for Tower 1 and Tower 2 were calculated to be 0.35 Hz and 0.32 Hz respectively. The calculated mode shapes were fitted with power relationships for dynamic deflection versus height, with exponents of 4.03 and 4.20 respectively. The structural damping was assumed to be 1% of critical, but this is exceeded by aerodynamic damping, which is about 4% of critical at ultimate limit states design wind speeds. The liquid damper in Tower 2 was assumed to provide damping of 3% of critical.

CALCULATION OF BENDING MOMENTS ACCOUNTING FOR DIRECTIONAL RISK

The ESWL method was used to calculate bending moments, shearing forces at three different levels, *s*, on each structure, together with the equivalent static load distributions corresponding to those load effects. For both structures, calculations were made for eight different wind directions – with four of these being normal to a face, and the other four were oblique wind directions along a diagonal. For towers like these the sizing of the four legs is governed by the oblique directions for which two legs lie on the neutral axis for bending. The normal wind directions govern the design of other structural members including horizontals and bracing members.

Figure 1 shows an example of the components and combined wind pressure distributions (i.e. the loads at each section divided by the frontal area projected normal to the tower face), for an oblique wind direction. The varying distributions of the mean, background and resonant components are clearly apparent in this Figure.

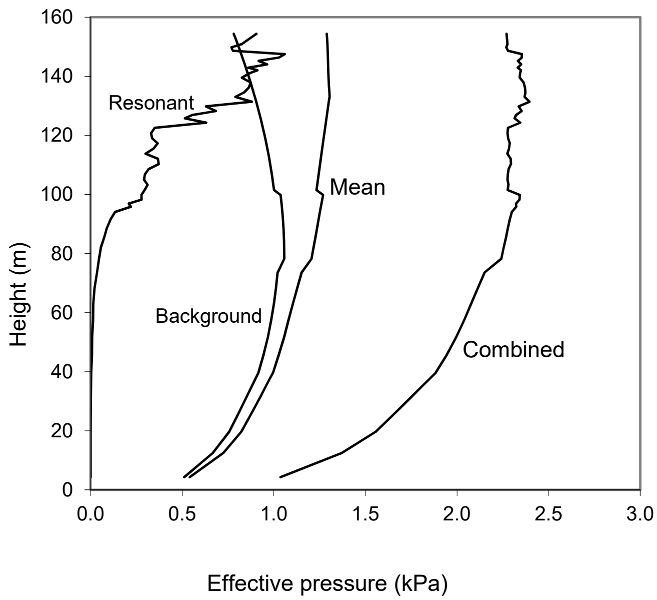

Figure 1. Effective pressure distributions for base moments (s = 0) on Tower 1
(SW wind direction - along a diagonal)

Of more relevance for design are the values of structural loads with a defined ARI, for extreme winds from any direction taking account of the directional probabilities of occurrence. To this end, bending moments and shear forces for the various directions were combined using the multi-sector method, and corresponding sectional load distributions generated.

The relationship between the bending moment in MN.m at each height level, and the gust wind speed at the reference position, was fitted with the form of Equation (3).

$$M = M_{o,i} \hat{V}_i^{\,n_i} \tag{3}$$

The index *i* indicates the wind direction. $M_{o,i}$ is a scale factor and n_i is an exponent; the latter are slightly greater than the 'normal' value for wind loading of static structures of 2.0, because of the effect of resonant dynamic response on the total bending moments, with the increment above 2.0 being greater as *s* increases, due to increased contributions from the resonant response.

The all-direction gust wind speed versus average recurrence interval, *R*, for *Regions A0* to *A5* in AS/NZS 1170.2 is given by Equation (4):

$$V_R = 67 - 41.R^{-0.1} \tag{4}$$

This can be adjusted for each of eight individual wind directions by Equation (5):

$$V_{R,i} = 67 - 41.[p(\theta_i).R_i]^{-0.1} \qquad (5)$$

where $p(\theta_i)$ is the directional probability of high wind speeds occurring within a directional sector, i.

Directional probabilities that are consistent with AS/NZS 1170.2 can be derived from the wind direction multipliers in *Table 3.2(A)* of the Standard, by inverting Equation (5) and substituting $V_R.M_{d,i}$ for $V_{R,i}$. Since the sum of the probabilities must equal 1.0, they may need rescaling to ensure that. As an example, for *Region A2*, the effective directional probabilities are given in Table 1.

Table 1. Directional probabilities for Region A2

Direction	N	NE	E	SE	S	SW	W	NW
M_d	0.85	0.75	0.85	0.95	0.95	0.95	1.00	0.95
$p(\theta_i)$	0.026	0.006	0.026	0.142	0.142	0.142	0.375	0.142

From Equations (3) and (5) it can readily be shown that the average recurrence interval for a particular bending moment, M, given winds blowing from a direction, i, is given by Equation (6):

$$p(\theta_i).R_i = \left[\frac{41}{67-(M/M_{0,i})^{1/n_i}}\right]^{10} \qquad (6)$$

The number of exceedances per annum, r_i, of the bending moment, M, for winds in a direction sector, i, is then the reciprocal of the directional ARI:

$$r_i = \left[\frac{67-(M/M_{0,i})^{1/n_i}}{41}\right]^{10} \qquad (7)$$

Then the total rate of exceedance considering N wind directions can be calculated as the sum of those from each direction sector included:

$$r_{total} = r_1 + r_2 + r_3 \ldots . = \sum_{i=1}^{N} r_i \qquad (8)$$

where N is the total number of directions included. Equation (8) is a variation of Equation (2).

The combined ARI for the moment, M, is the reciprocal of the rate, $(1/r_{total})$. The above equations are then be solved iteratively to determine the bending moment which matches the required ARI for design – for example 1000 years. Using this approach, the four directions with wind normal to a face were combined, and, separately, the four directions for which the wind blows obliquely along a diagonal. Thus 'N' in Equation (8) is taken as 4, instead of 8. This approach is justified because of the differing effects on the structure of the lattice towers of winds and drag loads normal to a face, and those along the diagonals, as discussed earlier. The recommended sectional and joint wind loads were obtained by taking weighted averages according to the directional probability, from the contributing wind directions, and then normalizing them to match the combined bending moments as described above. Shear forces were then calculated from the effective static load distributions.

COMPARISONS WITH WIND LOADS FROM AS/NZS1170.2

It is of interest to compare the calculations of bending moments using the combined ESWL/Multi-sector probability approaches, with the equivalent values calculated entirely from the Standard, AS/NZS1170.2.

Table 2 shows ultimate limit states (ULS) base moments (s = 0) in MN.m, calculated by the ESWL method for Tower 1, with values, for individual wind directions, compared with the equivalent moments calculated directly from AS/NZS1170.2. The latter method based on a *gust envelope* load distribution with height, as noted earlier. The average reduction ratio is 0.79 (21% reduction). There are several reasons for this, including the over-emphasis of the resonant response on the base moments by the Standard, and the neglect of aerodynamic damping,. The Standard also assumes a constant value of correlation coefficient between the background wind load at each tower section and the base moment.

Table 3 shows a similar comparison for the bending moment at s = 129.m, the top of the tapered sections of the tower. In this case the reduction factor (average of 0.84) is greater (i.e. less reduction from the use of the more accurate ESWL approach). This is mainly because of the greater contribution from the resonant loading on the upper sections of the tower on the bending moment at the upper cross section.

Table 2. Peak base moment (s = 0) comparisons for Tower 1

Direction	ESWL	1170.2	ratio
N	67.2	84.9	0.79
NE	79.2	100.2	0.79
E	76.9	97.8	0.79
SE	72.1	91.1	0.79
S	69.2	87.7	0.79
SW	82.2	103.3	0.80
W	62.9	80.0	0.79
NW	59.2	74.0	0.80

Table 3. Peak bending moment (s = 129 m) comparisons for Tower 1

Direction	ESWL	1170.2	ratio
N	1.27	1.51	0.84
NE	1.42	1.70	0.84
E	1.43	1.71	0.83
SE	1.37	1.64	0.84
S	1.30	1.56	0.84
SW	1.45	1.73	0.84
W	1.23	1.48	0.83
NW	1.15	1.37	0.84

The comparisons in Tables 2 and 3 do not include any allowance for directionality. That is, the wind direction multiplier, M_d, in AS/NZS1170.2 has not been applied, and the multi-sector method has not been applied to the calculations from the ESWL method. However, direction effects are included in Table 4, which compares the *maximum* predicted base moments for winds normal to a face, and those acting obliquely along a diagonal.

Slightly higher ratios of the ESWL/M-S predictions to those from the Standard are seen in Table 4, compared with those in Tables 2 and 3. This is because the wind direction multipliers in AS/NZS1170.2 are based on the directional response of main framing members in a low-rise building of rectangular plan, rather than a lattice tower. However, the reductions in predicted structural responses from the use of the combined ESWL/M-S methods are significant for the broadcasting towers. These towers are typically 60 years old and have had numerous antennas added over their life times. Although they have regular structural checking and maintenance schedules, any reduction in checking wind loads, resulting from applying a more rigorous method, is clearly beneficial in prolonging their life.

Table 4. Peak bending moment comparisons for Tower 1, including directionality

Case	*s* (m)	ESWL/M-S	1170.2	ratio
normal	0	65.3	80.0	0.82
oblique	0	77.0	92.0	0.84
normal	129	1.25	1.48	0.85
oblique	129	1.37	1.53	0.89

Similar comparisons for Tower 2 are shown in Table 5. In this case, the reductions in the base moment from the ESWL/MS method are lower: 4-6% . For the s = 100m, the top of the tapered section, the ESWL/M-S and the Standard give nearly identical values. However, if the effects of the liquid damper at the top of Tower 2, (included in both the ESWL calculations and those from the Standard), are removed from the calculations, the reductions in bending moments are similar to those for Tower 1.

Table 5. Peak bending moment comparisons for Tower 2, including directionality

Case	*s* (m)	ESWL/M-S	1170.2	ratio
normal	0	82.2	87.6	0.94
oblique	0	82.5	86.4	0.95
normal	100	11.93	11.91	1.00
oblique	100	11.60	11.65	1.00

SUMMARY AND CONCLUSIONS

1. The use of the Equivalent Static Wind Load (Extended LRC-ESWL) method, for tall lattice towers, correctly allows for the different vertical distributions with height of the mean, background and resonant dynamic wind load components, and allows for the inclusion of aerodynamic damping.
2. The Multi-sector (M-S) method is a simple and accurate method of accounting for the directional variation in extreme wind climate, and in the structural response.
3. Due to the symmetrical sizing of members, the logical way of allowing for the directional wind climate and the variation of tower response with wind direction, is to separate the directions acting normal to a face, from those acting along obliquely the diagonals. This was done for the two example towers discussed in this paper.
4. For one of the towers discussed (Tower 1), the combined ESWL/M-S methods produced significant reductions (11-18%) in predicted bending moment responses, compared with predictions made entirely using AS/NZS1170.2:2021, (Standards Australia, 2021),. Due to effect of the liquid damper, the predictions are closer (0-6% reductions by the ESWL/M-S approach) for Tower 2 .

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