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# Codification of wind loads on curved-roofed structures

Graeme Wood[1], Anton Lynar[2]

[1]Arup, Level 10, Sydney, NSW 2000, Australia, e-mail graeme-s.wood@arup.com

[2]Lynar consulting, Orange, NSW 2800, Australia anton@lynar.com.au

## ABSTRACT

The wind loading on large span roofs for structural design is not well covered in design standards such as AS/NZS1170.2. A series of simultaneous pressure measurement tests were conducted by Cermak Peterka Petersen on large span arch roofs mounted on the ground, with and without end walls. The simultaneous pressure results have been combined with structural characteristics to determine the overall pressure distribution across the roof causing peak structural responses. The results have been analysed and compared with published data to develop pressure distributions that could adopted by the Standard. This paper will present the findings of the study illustrating the importance of asymmetric loading and potential distributions for a range of arch roofs.

## 1. Introduction

Arched roofs are a common roof type on large buildings as they are structurally efficient allowing clear internal spans. There are Reynolds number modelling issues in testing these curved structures. Previous research has concentrated on the mean pressure distribution over these roof surfaces either averaged along the entire length of the structure or in segments. However, the pressure distribution causing the highest peak structural response is different to the mean distribution, particularly on a structure sensitive to asymmetric loads. The structural system used to support the roof is generally of true arch or portal frame construction and therefore the averaging performed by the wind engineering community is not necessarily approprate to the critical structural loading. Several failures of such structures are reported in Natalini et al. (2012) and cases have occurred in Australia.

The wind loading on these structures has been investigated by a number of researchers. The pressure coefficients in various wind standards around the world come from the works of Eiffel (1914), Bounkin and Tcheremoukhin (1928), Irminger (1936), Pris (1963), and Blessman (1998). Most of this work was carried out in smooth flow wind-tunnels.

The definition of geometry changes between the various Standards. Using the geometry defined in Standards Australia Figure 1, a comparative plot of external pressure coefficient is presented in Figure 2 and in Figure 3 for specific general cases. It is evident that there is a wide range of values for the various roof sections. Only the Australian Standard has a range of pressure for all roof section to accommodate for asymmetric wind loading.

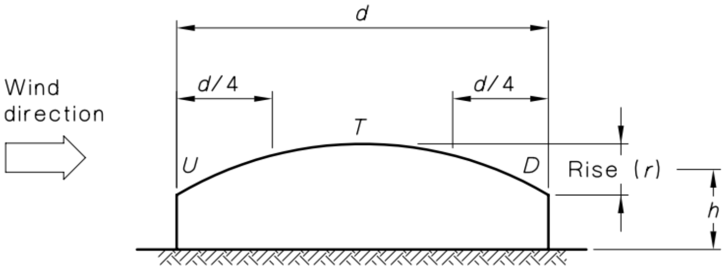


Figure 1: Definition of curved roof geometry from Standards Australia (2011)

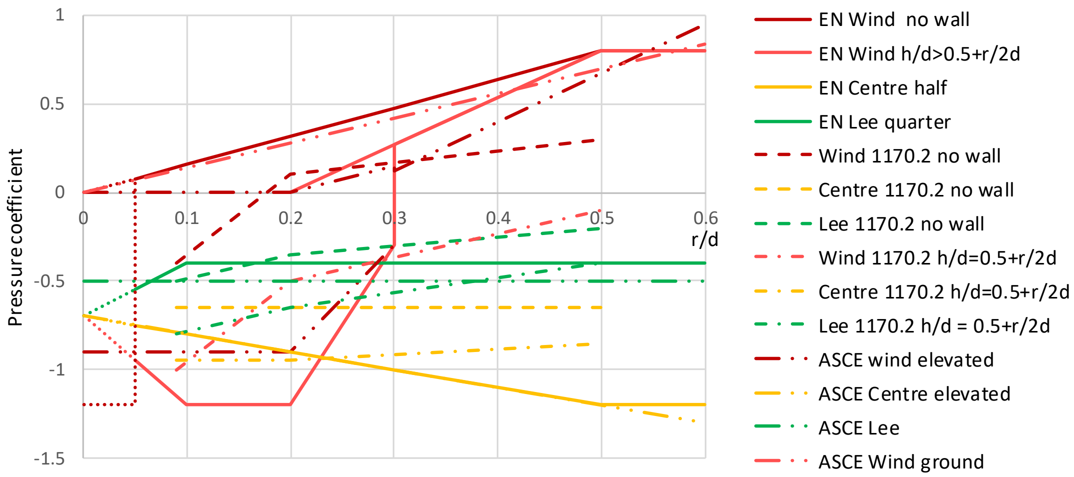


Figure 2: Comparison of various Standards for wind in quadrant normal to the ridgeline

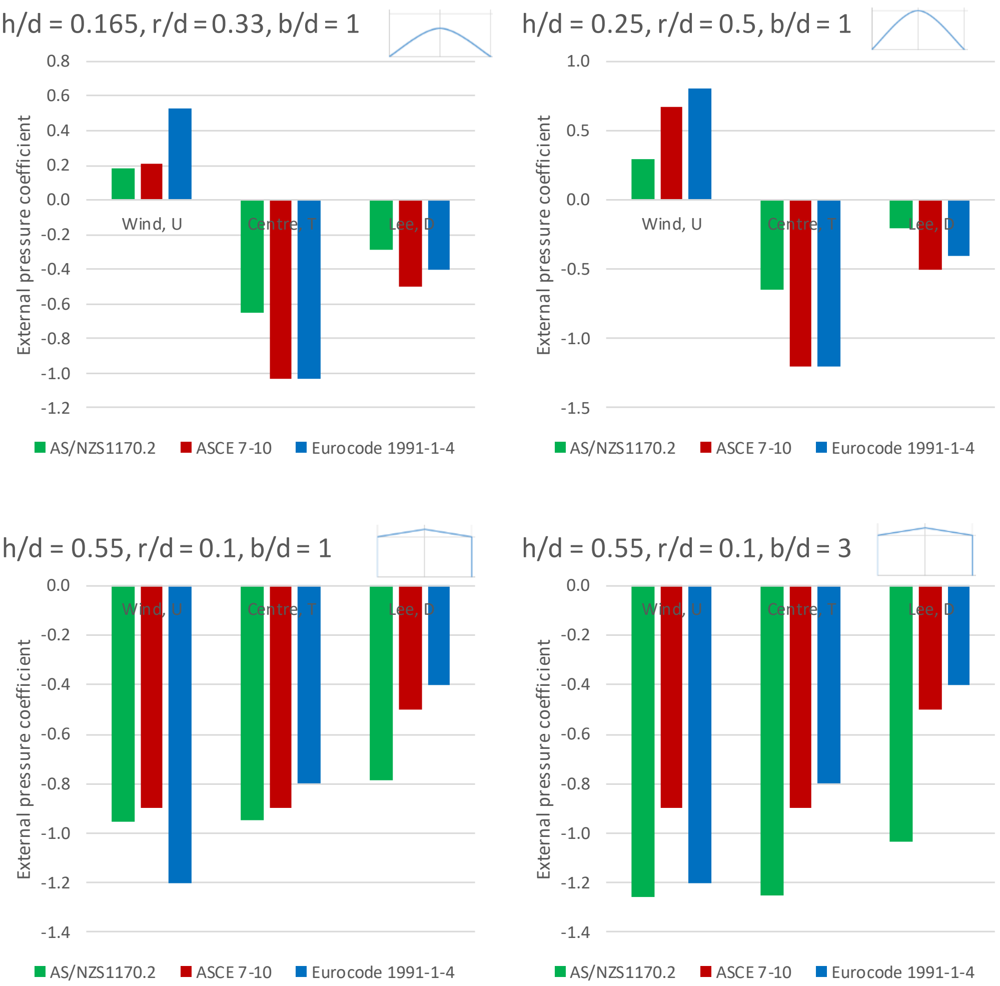


Figure 3: Comparison between external pressure coefficients from various Standards

The most extensive parametric study on the mean pressure distribution over curved roofs, raised on walls and mounted on the ground, and tested in isolation and adjacent to a neighbouring building was conducted by Blessman(1998). Typical section distributions at the windward, centre, and leeward section of the roof, for incident winds at 30° from normal to the roof ridge are presented in Figure 4. Assuming a quasi-steady process, it is evident that the averaging process used in the Standards along the length of the roof is omitting the localised peak pressures that have been measured in the separation zone on the roof. These local increased pressure are important for the asymmetric loading on such structures. These results are similar to Toy and Tahouri (1988).

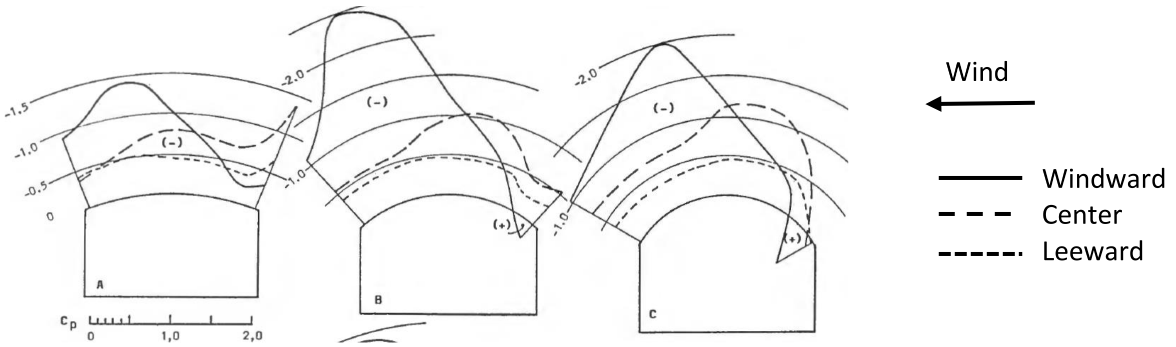


Figure 4: Mean pressure coefficient based on mean wind speed at roof crest height, Blessman (1998)

Blackmore and Tsokri (2006) conducted parametric testing to compare wind-tunnel results with the Eurocode. This study was conducted on models with a full-scale span of 25 m at a scale of 1:250 for a range of wall height (h/d 0/06->1), roof rise (r/d 0.05->0.5), and length of building (L/d 1->10). Averaged pressures were presented in the zones defined in Figure 5. Although not defined in the paper, the length of building used in the averaging is assumed to be 25 m full-scale.

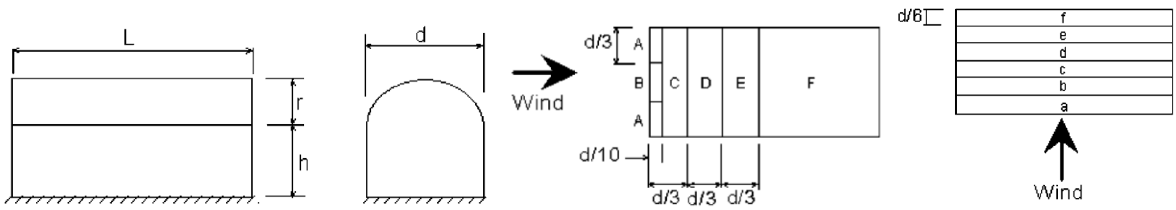


Figure 5: Definition sketch from Blackmore and Tsokri (2006)

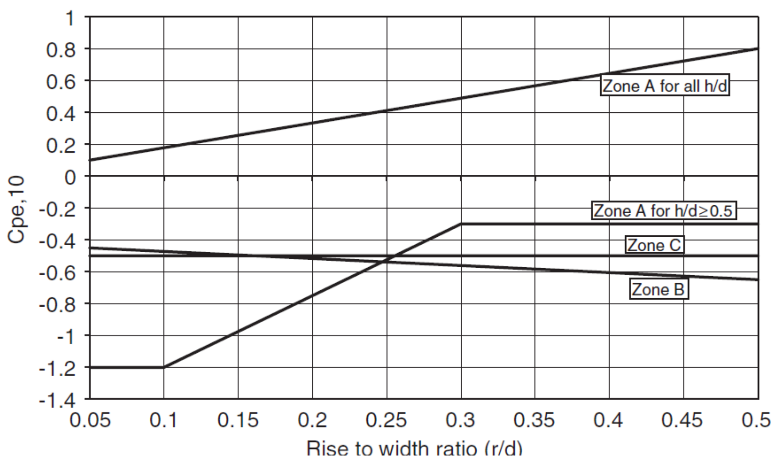


Figure 6: Proposed changes to Eurocode after Blackmore and Tsokri (2006)

More recent work was conducted on a free standing curved roofs at different heights by Natalini *et al.* (2009, 2013). The study investigated the mean pressures on a quarter of the arched roof. Pressure distirbutions over the windward and central section of the roof for an incident wind from 30° normal to the ridgeline are presented in Figure 7. Similar to the work of Blessman, the circumferential mean pressure coefficient distribution is considerably different to the format presented in the Standards.

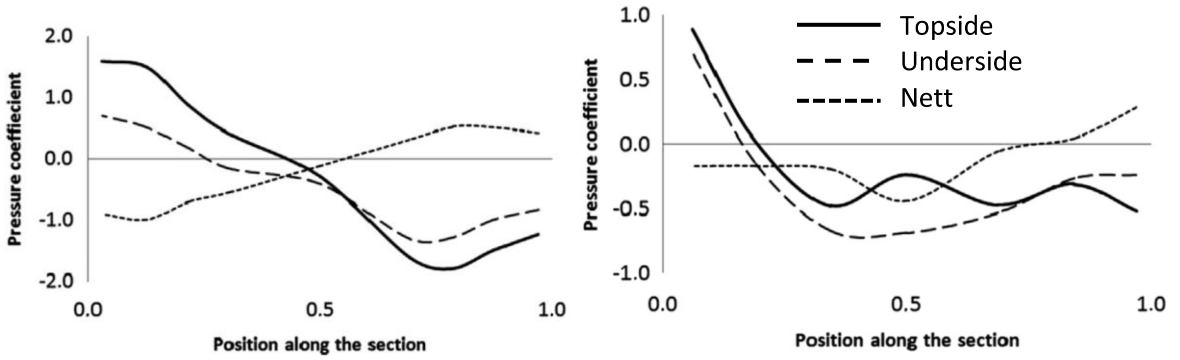


Figure 7: Mean pressure distribution along windward section (L) and central section (R) of a free canopy curved roof (after Natalini et al. 2013)

## 2. Results

Wind-tunnel testing was conducted by Cermak Peterka Petersen on a range of curved roof types in a closed and open configuration. Only the results of the closed building configuration will be discussed herein for comparison with the various Standards. The wind-tunnel testing and findings were presented in Noguez-Ceron et al. (2016). An influence coefficient analysis was conducted to determine peak responses along a true arch structure, with the corresponding pressure distribution across the roof. The results showed that the peak bending moments along the arch were about four times greater than would have been estimated using the pressure distribution from Standards Australia (2011). Using this data, and averaging in accordance with the various Standards, Figure 1,the peak pressure in each roof zone resulting in the peak member response for winds within ±45° of normal to the ridgeline are presented in Figure 8.

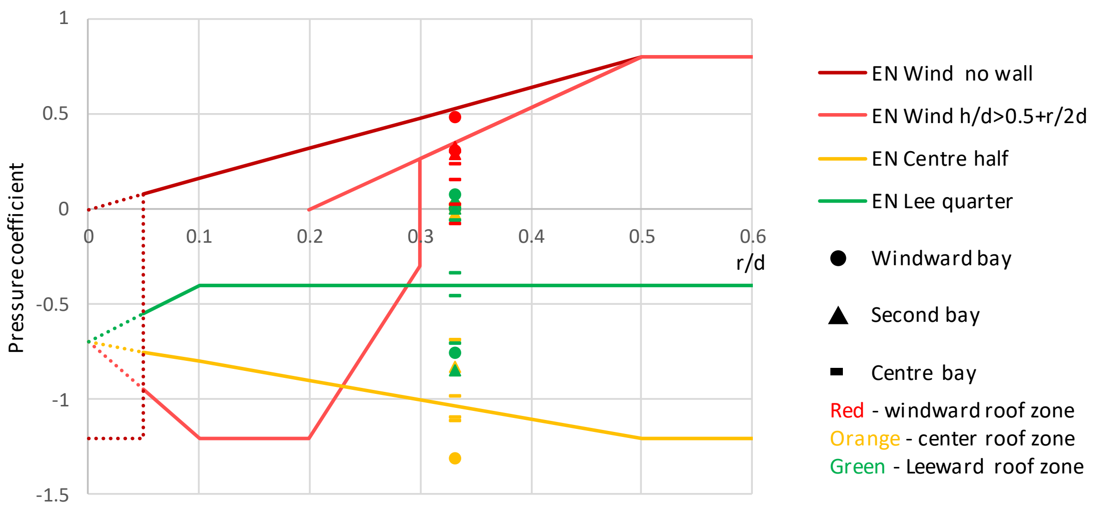


Figure 8: Comparative pressure coefficient results with the current Standard

It is evident from Figure 8 that the Eurocode is conservative for the windward roof zone, but is non-conservative for the centre and leeward zones. The pressure distribution associated with the peak responses for winds with the ±45° quadrant are presented in Figure 9, where segment 13 is to the windward corner. The peak load is by incident winds from 20-40° from normal to the ridgeline, resulting in separation from the gable end of the structure. The results are similar in form to the mean distributions of Blessman (1998), Figure 4. This local mechanism would be filtered through averaging along the length of the structure rather than taking an instantaneous snapshot of the pressure distribution. The constant pressure for the central half of the curved roof is non-conservative for structures susceptible to asymmetric wind loading.

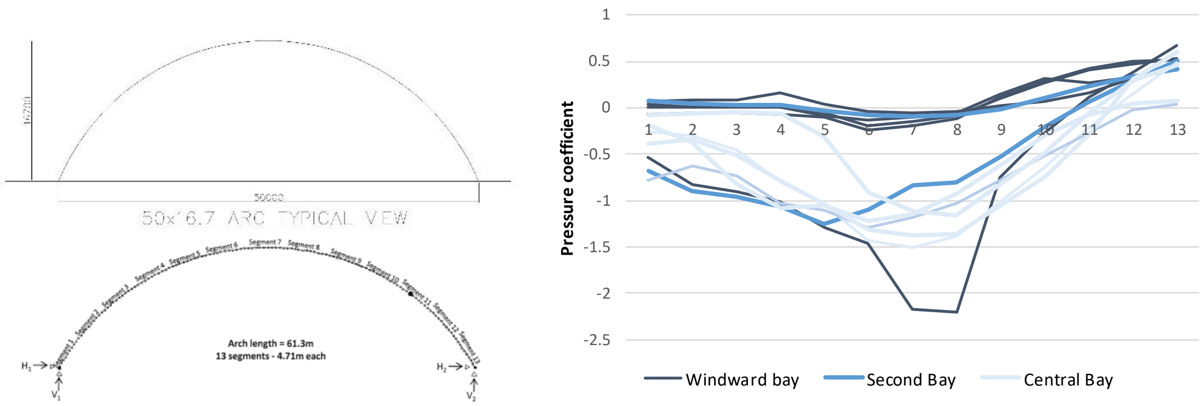


Figure 9: Sectional dimensions of the curved roof and pressure coefficient distribution resulting in peak member responses

It would be expected that the size of the structure relative to the scale of turbulence and the flow characteristics would influence the critical wind loading pattern for the structure. For example, the importance of local pressures acting on a 10 m span roof with frames at 5 m spacing, would be considerably different to a geometrically similar roof spanning 50 m with frames at 10 m spacing. These considerations may have to be addressed by the Code committee investigating this section of the Standard.

## 3. Conclusions

An initial study has been conducted with the aim to update Clause C3 of Standards Australia (2011), for external pressure coefficients on enclosed curved roofs. It is evident from the available published data that only a limited amount of wind-tunnel testing has been conducted on curved roofs. The flow characteristics and resulting fluctuating wind loads over a curved surface are exceptionally complicated. The added complication of the underlying structural system to resist the wind loads has to be taken into consideration. It is considered that most of these structures are typically designed as portal frames, and therefore a pressure distribution along the length of the structure would be non-conservative if averaged over a distance greater than the portal frame spacing distance.

Results from structural wind-tunnel testing on a large curved roof illustrated that the wind loading distributions in the relevant Standards are potentially non-conservative, particularly on the end Bay and in the central section of the roof where a uniform load case is specified. This loading is critical for structural systems sensitive to asymmetric loading. Unfortunately, there is insufficient reliable wind-tunnel data currently available to update the Standard for all cases.

The structural systems supporting smaller roofs are generally lighter and structurally optimised, hence are more susceptible to local pressure factors. These factors need to be considered in any revision of the code.

## References

ASCE (2010),

Blackmore, P.A., and Tsokri, E. (2006), Wind loads on curved roofs. J.Wind Eng. Ind. Aero. Vol. 94, pp.833-844.

Blessman, J., 1998. Wind loads on isolated and adjacent industrial pavillion curved roofs. Wind effects on Buildings and Structures. Riera & Davenport. Balkema, Rotterdam, pp.137–171.

Bounkin, K., and Tcheremoukhin, A. (1928), Wind Pressures on Roofs and Buildings. Transactions Central Aero and Hydrodynamical Institute, Moscow, No.35.

Eiffel, G., 1914. Nouvelles recherches sur la résistance de l'air et l'aviation faites au laboratoire d'Auteuil. H. Dunod et E. Pinat, Paris.

Eurocode (1998),

Holmes, J.D., 1984. Determination of wind loads for an arch roof. Inst. Eng. Aust. Civ. Eng. Trans. CE26, 247–253.

Irminger, J.O., Nökkentved, C., (1936). Wind Pressure on Building. Experimental Researches Second series. Naturvidenskabelige Sanfund, Copenhagen.

Natalini, M.B., Morel, C., Natalini, B.,and Canavesio, O., (2009) Mean loads on vaulted canopy roofs: tests in boundary layer wind tunnel. 11th Americas conference on wind engineering, San Juan, Puerto Rico.

Natalini, M.B., Morel, C., and Natalini, B., (2013) Mean loads on vaulted canopy roofs. J.Wind Eng. Ind. Aero. Vol.119, pp.102-113.

Natalini, B., Lassig, J.L., Natalini, M.B., and Palese C., (2012), Damaging wind storms in North Eastern Argentina: seven case studies, Wind and Structures, Vol.15, No.2, pp.147-162.

Noguez-Ceron, M., Wood, G.S., and Lynar, A. (2016), Asymmetric wind loading on large roof structures. 18th AWES Workshop, McLaren Vale, South Australia)

Pris, M.R., 1963. Études aerodynamiques VII: Determination des pressions dues a l'action du vent sur les toitures des bâtiment rectangulaires en plan en contact avec le sol. Ann. Inst. Tech. Bâtiment Trav. Publics, Vol.186, pp. 589–620.

Standards Australia, (2011), "Structural design actions. Part 2 Wind actions", Australian/New Zealand Standard, AS/NZS 1170.2:2011.

Toy, N., and Tahouri, B., (1988), Pressure distributions on semi-circular structures of different geometrical cross-sections. J.Wind Eng. Ind. Aero. Vol.29, pp.263-272.