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Wind loads on buildings with vaulted roofs and side walls – A review

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ABSTRACT

The recommendations of the Argentinean code of practice CIRSOC 102 concerning wind loads on enclosed buildings with curved roofs are identical to those of ASCE 7, which are based on results published in 1914. Significant differences can thus be expected if this treatment is compared with an updated bibliography. This paper reviews the information available in the open literature, including a number of significant studies written in Portuguese that are not readily accessible, with the CIRSOC 102 treatment then compared with state-of-the-art results. The need to update the code is shown, possible criteria and values are suggested, and research needs are listed.

1. Introduction

The barrel-vaulted roof is one of the most common design choices in South America for large industrial or commercial buildings. Every year a number of these structures collapse under wind loads (Blessmann, 1986; Balbastro and Sonzogni, 2008; Natalini et al., 2012). The way in which the Argentinean code of practice CIRSOC 102 (CIRSOC, 2005) estimates design wind loads on buildings with vaulted roofs and side walls (VRSWB) is based on Albert Smith's (1914) model, which can be considered the first of its kind ever proposed. This formulation is derived from the measurement of pressures experienced by large models exposed to natural wind (Smith, 1914). Smith was able to overcome the difficulties posed by the limited conceptual and physical tools available at the time, and even though more studies have since been published, Smith's model is still in use in both the CIRSOC 102 and ASCE 7–10 codes.

Data in the literature regarding VRSWB are frequently reported and discussed together with those on arched roofs springing from ground level (ARSGL). Here, previous work examining both morphologies will be listed, but the following discussion will focus only on VRSWB. Contemporary to Smith's studies were the wind tunnel tests of Eiffel (1914) that were carried out in his laboratory at Auteuil. Eiffel tested models of airship hangars with pointed arch cross-sections (pointed barrel vaults), describing the effect of different ventilation devices and openings on the wind pressure distribution.

Among the earliest wind tunnel studies that followed included those of Coupard (1927), Bounkin and Tcheremoukhin (1928), Arnstein (Watson, 1930), Allard (Baes and Verdeyen, 1932), Irminger and Nökkentved (1936), Chien et al. (1951) and Pris (1963). According to Holmes (1984), Bounkin and Tcheremoukhin's study formed the basis for the recommendation contained in the 1983 edition of the Australian code AS 1170. The French code NV 65 (1970) was based on Pris' tests, with this treatment in turn employed in the Argentinean code CIRSOC 102 (1983) that was in force until 2012. All of the tests listed above were conducted under uniform mean flow, with low turbulence levels. However, apart from their value in documenting the history of building aerodynamics, these data today have limited applications for codification purposes because they do not take into account the influence of the atmospheric boundary layer.

The first wind tunnel test using atmospheric wind simulation dates from 1981, when Wong (1981) tested six ARSGL models at the University of Surrey, obtaining mean pressures under three different wind directions. Although Wong comprehensively addressed the proper reproduction of the Reynolds number effect, he failed to reproduce the highest suctions observed near the ridge of full-scale greenhouses. Ng (1983) reported local and spatially averaged external pressures on five models, as well as internal pressures on three of them. Mean and fluctuating pressures were measured, with three of the models also having side walls. All models were exposed to both open country and suburban boundary layer simulations during experiments carried out at the University of Western Ontario (UWO). Although Ng deserves credit for the care put into the experimental details and the synthesis of the results in arriving at a simplified load model, his results show certain discrepancies with full-scale data (and with that of other authors), attributed to differences in Reynolds numbers. In order to confirm this hypothesis, Johnson et al. (1985) tested (also at UWO)

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three semi-cylindrical models of increasing size, the smallest being similar to one of Ng's models. A distinct influence of the Reynolds number was verified, but the authors acknowledged the need to produce more experimental data in order to reach a complete understanding of the issue.

Meanwhile, Holmes (1984) tested the model of a hangar (VRSWB) in the wind tunnel at James Cook University, determining the peak values of the arch support reactions from fluctuating pressures measurements. The loads obtained in this way did not grossly differ from those derived from the Australian Standard AS 1170 in force in 1983, at least for the normal-to-the-eave wind direction, which was the only direction taken into account by the code. However, Holmes pointed out that the highest local loads occur for oblique wind, a feature already noted by Ng (1983). The model corresponded to an existing building under refurbishment, with its shape differing from that of conventional buildings by the presence of two protruding lateral corridors.

In 1987, the first two reports from a series of wind tunnel studies carried out at the Universidad Federal de Rio Grande do Sul (UFRGS), Brasil, were published. The CT-86 report (Blessmann, 1987a) presented local and global mean pressures on six VRSWB models for wind directions varying every 15 degrees, while the CT-88 report (Blessmann, 1987b) examined neighbouring effects using two identical VRSWB models with different aspect relations than those of CT-86. The results presented in these two reports were later quoted by Cook (1990), and from there by a number of different authors. The CT-94 report (Blessmann and Loredo-Souza, 1988) presented the results for another five models, three with side walls, while the CT-95 report (Blessmann and Loredo-Souza, 1989) presented results for nine VRSWB models. In total, this group of experiments produced data on nineteen VRSWB and two ARSGL models, with the results for incoming wind at 0°, 45°, 60° and 90° plus neighbouring effects for a variety of combinations of models J to R published by Blessmann in 1998.

Toy and Tahouri (1988) reported mean wind loads on models of ARSGL greenhouses with three different cross-sections: semi-cylindrical, pointed barrel vault and a combination of semi-cylinders with flat roofs. These models were tested in the wind tunnel at the University of Surrey under wind simulation. However, both Blessmann (1991) and Holmes and Paterson (1993) subsequently pointed out that the applicability of these results to full-scale structures may be questionable because of the high value of the Jensen number and low value of the Reynolds number. Cheung et al. (1992) reported mean and rms pressure coefficients from wind tunnel tests with wind simulation carried out at Monash University. Holmes and Paterson (1993) conducted a parametric study of mean pressures using a Computational Fluid Dynamics (CFD) model. Data produced by this CFD model were then compared with the results of Cheung et al. for validation. The results of the latter two studies form the basis of the current treatment of the Australian/New Zealand AS/NZS 1170.2:2011 code. Wittwer et al. (2002) reported mean pressure distributions on a model of an existing hangar tested at the Universidad Nacional del Nordeste (UNNE) wind tunnel. The model hangar had two laterally protruding corridors, similar to that tested by Holmes (1984), with the effect of these corridors on the mean pressure distribution also previously tested by De Bortoli et al. (2000) and Wittwer et al. (2000). Wittwer et al. (2004) later reported mean and peak point pressures on the same hangar but without lateral corridors. All the UNNE tests used properly scaled wind simulation. Franchini et al. (2005) tested four models in the wind tunnel at the Universidad Politécnica de Madrid in order to study the effect of roof curvature on the delta-wing vortices appearing under oblique wind directions, as well as the effectiveness of attenuation devices such as parapets. A low-turbulence wind simulation was used and only mean pressures were presented.

Blackmore and Tsokri (2006) carried out a comprehensive parametric study at the Building Research Establishment (BRE), UK. Twelve VRSWB models were tested, some with added dummy models in order to examine the effect of building length. Apart from their variety of geometries, these experiments are particularly important as they employed all the state-of-the-art techniques available for the wind tunnel modelling of these types of structure, including wind tunnel simulation appropriate to the scale of the models, the application of sand on the model roof, multipoint instantaneous measurement and determination of peaks via the extreme value methodology of Mayne and Cook (1979) and Cook (1982). Previously, tests reported by Breeze et al. (2004) were conducted on smooth-roofed models in investigating the effect of flow under subcritical conditions.

Yang et al. (2013) conducted tests on a model of a cladded building with an elliptical roof using proper wind simulation, with point mean pressures measured at facilities belonging to Nanjing University of Aeronautics and Astronautics. Qiu et al. (2014) reported mean pressures on six smooth-roofed VRSWB models tested at the Harbin Institute of Technology, China. The authors also proposed a model with which to predict loads for different rise/span ratios, although its application is limited to the conditions of the conducted experiments, that is, mean values, normal-to-the-eave wind direction, uniform flow, low turbulence and without consideration of the effect of the rise/eave height ratio.

A few well-known full-scale studies can be found in the literature, all of which focus on ARSGL. For example, Arnstein and Klemperer (1936) measured mean pressures on the Akron airship hangar, while Grillaud (1981) reported wind loads on an inflatable structure. Hoxey and Richardson (1983, 1984) reported the most important milestone so far regarding the analysis of ARSGLs, measuring fluctuating pressures and strains in the structures of six different film-plastic greenhouses. The review presented here started with Smith's, 1914 work, which was neither a wind tunnel nor a conventional full-scale study. We will close this section by mentioning another study that also does not belong to either of the two conventional research categories, in this case the work of Robertson et al. (2002), who conducted analysis of a full-scale greenhouse in the Jules Verne wind tunnel belonging to the CSTB, France.

In South America, most research is focused on VRSWBs due to the relative scarcity of ARSGLs in the region. Although the two share some aerodynamic features, they constitute different typologies. Whereas in ARSGLs the position of both the separation and reattachment points depends only on the Reynolds number, in VRSWBs the relative size of the walls plays just as important a role. Flow around VRSWBs is also more three dimensional and hence more complex. If studies focussing on structures with side walls are highlighted, it becomes clear that the group of experiments carried out by Blackmore and Tsokri at the BRE and by Blessmann and Loredo Souza at the UFRGS are the most relevant for codification purposes. Indeed, these studies were specifically designed with that aim in mind and examine a wide range of sizes. The authors were also aware that no full-scale data were available with which to validate their results and consequently they made sure that the setting of the tests was in agreement with state-of-the-art modelling.

In the present paper, the results of these experiments are discussed and compared with the CIRSOC 102 treatment (which is identical to ASCE 7–10), research needs are listed, and possible criteria and values appropriate for updating the codes are provided.

2. Data sources

2.1. Blessmann and Loredo Souza experiments

These experiments comprise wind tunnel tests carried out on nineteen models whose aspect ratios are summarised in Table 1. The nomenclature used here for the geometry of buildings is displayed in Fig. 1. The tests were carried out in the wind tunnel at the Universidade Federal do Rio Grande do Sul (UFRGS), a closed return boundary layer wind tunnel with a test section of 1.30 m width×0.90 m height and

Table 1
Details of the models tested at UFRGS. The original nomenclature is retained.

Model	Dimensions				Ratios			
	a [cm]	b [cm]	h [cm]	f [cm]	f/b	h/b	a/b	Re $\times 10^{-5}$
A				1.6	0.1			6.5
B	64	16	8	3.2	0.2	0.5	4	3.8
C				4.8	0.3			2.8
D				1.6	0.1			5.5
E	64	16	4	3.2	0.2	0.25	4	3.3
F				4.8	0.3			2.7
G				1.6	0.1			5.9
H	64	16	1.6	3.2	0.2	0.1	4	3.4
I				4.8	0.3			2.8
J				1.6	0.1			6.3
K	32	16	8	3.2	0.2	0.5	2	3.7
L				4.8	0.3			2.9
M				1.6	0.1			5.6
N	32	16	4	3.2	0.2	0.25	2	3.3
O				4.8	0.3			2.8
P				1.6	0.1			6.0
Q	32	16	1.6	3.2	0.2	0.1	2	3.5
R				4.8	0.3			2.8
CT-88	87.2	17	1.82	5.7	0.34	0.11	5.1	2.0

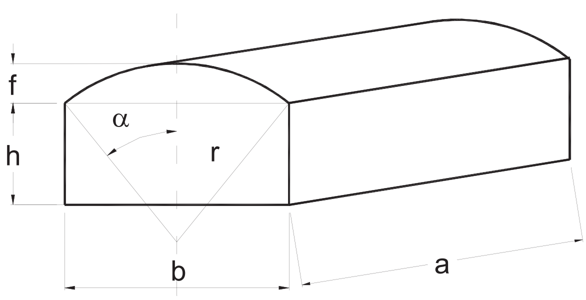

Fig. 1. Geometry nomenclature.

9.32 m in length. A detailed description of the tunnel can be found in Blessmann (1982). Tests were conducted under both uniform mean flow and wind simulation, with the latter in agreement with the flow over rural and suburban areas. Sand was added to the upper side of the model roofs in order to reproduce the appropriate flow regime. Point mean pressure coefficients were determined for incoming wind varying every 15 degrees. Area-averaged pressure coefficients were obtained for the six zones shown in Fig. 2a only for incoming wind from 90° (normal-to-the-eave direction), and for the zones shown in Fig. 2b only for incoming wind from 0°.

Table 2
Details of the models tested at BRE. The original nomenclature is retained.

Model	Dimensions				Ratios		
	a [cm]	b [cm]	h [cm]	f [cm]	f/b	h/b	a/b
R3B1			0.6			0.06	
R3B2			5	0.5	0.05	0.50	
R3B3			10			1.00	
R4B1			0.6			0.06	
R4B2			5	1	0.1	0.50	
R4B3	10	10	10			1.00	1
R5B1			0.6			0.06	
R5B2			5	3	0.3	0.50	
R5B3			10			1.00	
R6B1			0.6			0.06	
R6B2			5	5	0.6	0.50	
R6B3			10			1.00	

2.2. Blackmore and Tsokri experiments

Blackmore and Tsokri tested twelve models in BRE boundary layer wind tunnel no. 3, with dummy extensions used in some of the tests in order to investigate the effect of building length. Table 2 shows the aspect relations of the tested models. BRE wind tunnel no. 3 is an open return tunnel with a test section of 2 m width×1.5 m height and 20 m in length; a full description of the tunnel can be found in Parkinson and Cook (1992). A wind simulation in agreement with open country terrain was used and sand added to the roofs of the models. Simultaneous multipoint pressure records were obtained at 15° wind direction increments, as well as mean and 1 s (full-scale equivalent) peak pressures. Following Blessmann, Blackmore and Tsokri also zoned the roof into six strips (Fig. 2a) and presented the worst-case area averaged values for wind directions between 90° ± 45°. For wind directions between 0° ± 45° the authors used the zoning scheme shown in Fig. 2c.

2.3. Data compatibility

The data provided by Blessmann and Loredo-Souza are time-averaged coefficients, also known as quasi-static coefficients, which quantify mean loads. The estimation of designed wind loads using quasi-static coefficients requires the framework of the first order quasi-steady assumption, which assumes that pressure fluctuations on the building are linearly related to the fluctuation of the reference dynamic pressure, or to put it another way, it is assumed that the incident wind gusts fully explain the pressure fluctuations on the building. This

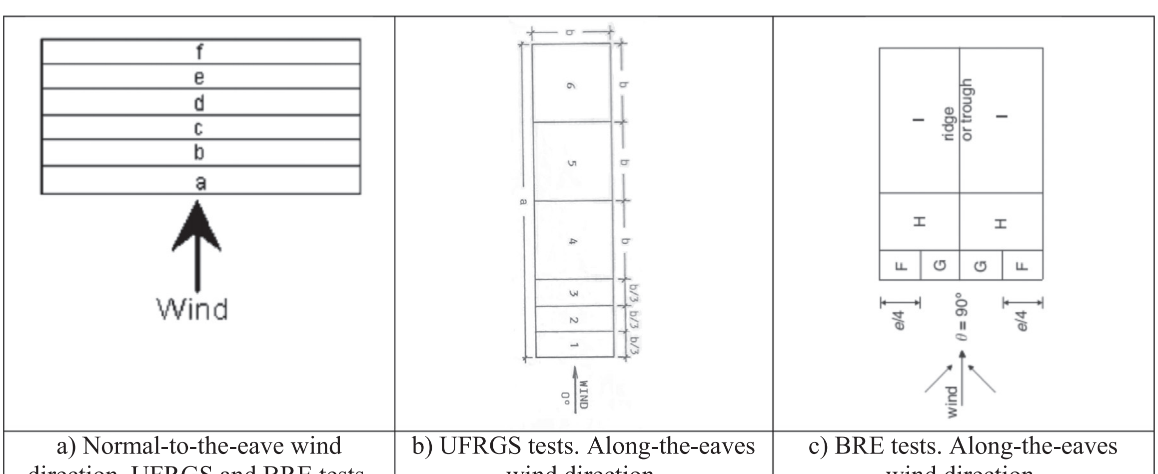

Fig. 2. Definition of loaded areas for MWFRS loads. a) Normal-to-the-eave wind direction. UFRGS and BRE tests, b) UFRGS tests. Along-the-eaves wind direction, c) BRE tests. Along-the-eaves wind direction.

assumption in turn implies that building-generated turbulence has no effect on the pressure fluctuations, with the model resulting from this assumption known as the equivalent-steady-gust (ESG) model. The accuracy of the ESG model has been discussed by Cook (1990), Letchford et al. (1993) and Hoxey et al. (1996), among others. In general terms, it is accepted that the ESG model acceptably represents global loads but misrepresents local loads in areas affected by building-generated turbulence. Today, ideal assessment models are preferred, which establish load coefficients for given exceedance probabilities from extreme value analysis of the fluctuating loads. Blackmore and Tsokri used the Mayne and Cook method, which is an ideal model. Even though a recommendation based only on quasi-static coefficients is not currently considered acceptable for codification purposes, it is still possible to extract a wealth of information from mean coefficients. However, it is also acknowledged that this must be done in a context in which the scope and limitations of the ESG model can be distinguished.

A comparison between the load coefficients used by ESG and ideal models is not straightforward. For a single point, whereas the ESG model uses a single mean value (a quasi-static coefficient) the Mayne and Cook model uses two peaks: a maximum and a minimum. These values can be either one positive and one negative, both positive, or both negative. In order to make such a comparison possible, the maximum and minimum coefficients are divided by the square of the gust factor measured in the experiment. This approach produces so-called pseudo-static coefficients, which are compatible with the ESG model despite arising from pressure fluctuations. A valid comparison can then be performed between the quasi-static and pseudo-static coefficients. As most codes of practice are ESG based, they frequently contain results derived from ideal models in the form of pseudo-static coefficients.

3. Data comparison

3.1. Loads on the main wind frame resistant system (MWFRS) with wind normal to eaves

There is a significant difference between the two data sources that must be considered before any analysis of coefficient values is undertaken. Whereas the CIRSOC 102 code divides the roof into three parts – the upwind quarter, the central half and the downwind quarter – both Blessmann et al. and Blackmore et al. divided the roof into six even parts (Fig. 2) and provided area-averaged suctions on the upwind, central and downwind thirds.

3.1.1. Suctions on upwind zones ‘a+b’

Fig. 3 shows upside pressure coefficients on area *‘a+b’* for a span/length ratio a/b =1. As the UFRGS models employ a ratio of a/b=2, a factor of $1-(\frac{a}{b})^{0.25}$=0.19 was here summed to the UFRGS values. This correction is based on BRE results for models with different lengths.

The discussion in this subsection is restricted to the lower part of Fig. 3, i.e. that corresponding to negative values. It is clear that the values of the CIRSOC code do not represent even approximately the experimental values, with the exception of those in the interval 0.2≤ f/b≤0.3, which are close to the BRE values for h/b=1. For f/b≥0.3, CIRSOC 102 does not specify any suction values. Two basic alternative updating criteria can be proposed: a simple criterion, erring well on the side of safety and represented by a single envelope, or a more detailed criterion combining BRE and UFRGS data, which would allow for more cost-effective designs. Blackmore and Tsokri proposed the envelope represented by the black dashed line in Fig. 3. Note that although this recommendation was proposed for h/b ≥0.5, it could also be extended to buildings with h/b < 0.5 on the side of safety.

It can be observed from this figure that there are only two experimental points for aspect relations f/b below 0.1. Balbastro (2009) surveyed the aspect relations of about 300 buildings in northern Argentina, demonstrating that 90% were characterised by values of f/b

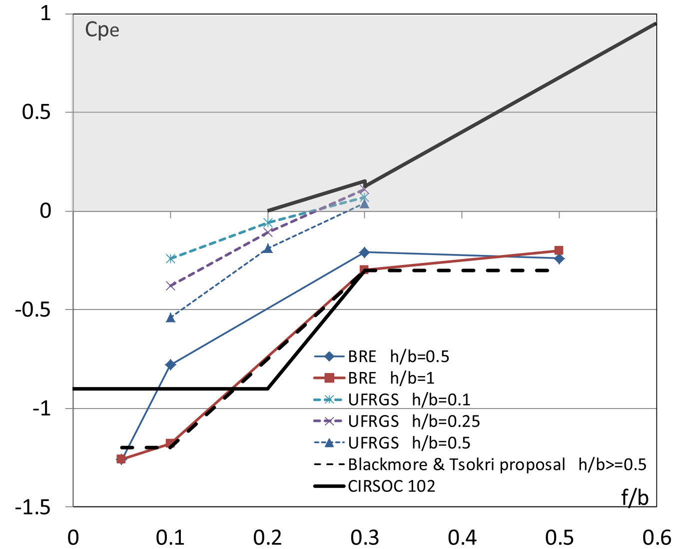

Fig. 3. Loads on the MWFRS under normal-to-eaves wind. Suctions on upwind zones ‘a+b’.

between 0.07 and 0.18. Taking into account the evidence for the existence of a sharp increment in suction for f/b < 0.1, it is apparent that more data are required regarding this part of the figure. It is also interesting to note that prior to the publication of BRE results, Cook (1990) recommended load assessment to be carried out as if the roof were flat, using the rules for ‘Flat roofs with sharp eaves’. Following this criterion produces values of −1.47≤ Cp ≤−1.15, a range that is in agreement with the BRE data. More data are also required in the interval 0.1 < f/b < 0.3, for which the only data are those of UFRGS for f/b=0.2, which show that design loads could be reduced provided more information in that range is produced.

3.1.2. Positive pressures on upwind zone ‘a’

Fig. 4 shows the positive coefficients for zone *'a'*. Although CIRSOC values are in agreement with a limited amount of UFRGS results in the range 0.1 < f/b < 0.3, the BRE values reveal that the CIRSOC recommendation underestimates the loads. The UFRGS results were not corrected to take into account the difference in the a/b ratio because, according to Blackmore and Tsokri (2006), positive pressure in this area appears to be independent of a/b. The BRE values display a

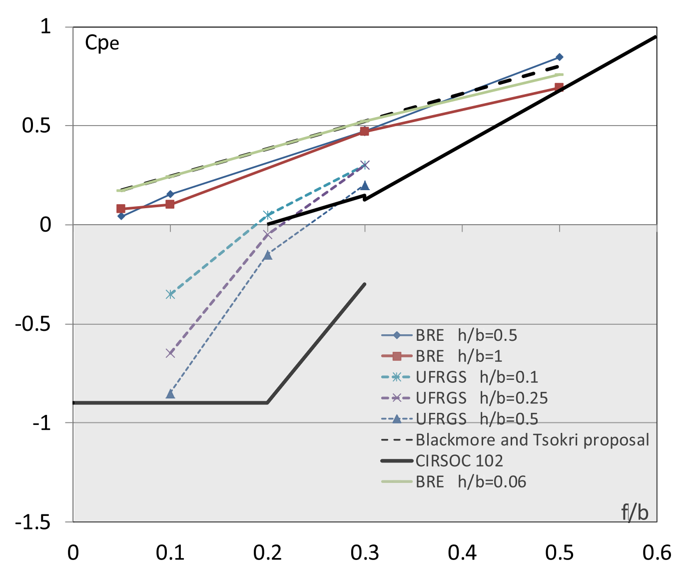

Fig. 4. Loads on the MWFRS under normal-to-eaves wind. Positive pressures on upwind zone ‘a’.

weak dependency on h/b and vary linearly with f/b, with the envelope proposed by Blackmore and Tsokri thus seeming to be the obvious option for updating the CIRSOC treatment.

3.1.3. Suctions on central zones 'c+d'

Fig. 5 shows suctions calculated for zones *'c+d'*. Although BRE values are less severe than those of UFRGS, the CIRSOC recommendation overestimates loads with respect to both sets of results. This part of the roof lies downwind from the separation point and the pressure fluctuations are thus partially due to generated-by-the-structure turbulence, a situation unfavourable for the performance of the ESG model. It was expected that UFRGS values reveal a more severe picture than those of BRE because the former data correspond to a/b=2. Correction was not applied since the variation of the load coefficients with the a/b relation is non linear and a precise rule to move from a/b=2 to a/b=1 is not available. Blackmore and Tsokri provided a correction criterion that is useful when designing a structure, but this criterion is not suitable for use in the present analysis in which different experiments are compared. For these reasons, the BRE data should be selected as reference values. For codification purposes a single envelope could be used, with the simplest proposal a uniform value of Cp=−0.75, or three curves for different h/b relations. Fig. 5 shows that further information is required for f/b < 0.1 and 0.1 < f/b < 0.3. The use of Cook's rules for f/b < 0.1 would lead to values of Cp≅−0.7, close to the CIRSOC recommendation.

3.1.4. Suctions on downwind zones 'e+f'

Fig. 6 shows suctions on zones *'e+f'*. According to Blackmore and Tsokri, correction to account for differences in the a/b relation appears to be unnecessary in this case. As with the central zones, and for the same reasons, BRE values should be taken as reference. The single-envelope CIRSOC recommendation is coincident with Blackmore and Tsokri's suggestion. Again, three curves for different h/b relations would allow for a reduction in loads in some cases.

3.2. Loads on the MWFRS with wind parallel to the eaves

In this case the CIRSOC code recommends the adoption of values corresponding to duo-pitch planar roofs. The values appearing in the code are derived from wind tunnel tests performed under uniform mean flow and low turbulence, in which two wind directions were tested: normal and parallel to the eaves. According to the code, both the magnitude and influence area of the coefficients depend on the eave height, h. Blackmore and Tsokri stated that ' ...the measured data are actually only very weakly dependent on h...'. Indeed, UFRGS pressure coefficients vary on average by 0.04 with h, a pattern consistent with the Blackmore and Tsokri comment. Thus, the implicit assumption that h is a relevant variable for vaulted roofs has no grounds. On the other hand, there is experimental proof that roof length, a, must not be used as a scaling parameter with which to define the influence areas. Fig. 7 shows the distribution of the area-averaged pressure coefficient along the roofs of two of the UFRGS models (Blessmann, 1998): model J and model A. Both models are identical in section (see Table 1) but model A is twice as long as model J. If the distance along the roof is scaled by the span, b, the load distributions of the models do not differ significantly.[1] In Fig. 8 the same information is displayed, but the abscissa axis is in this case scaled by the length, a, instead of the span. This single change in the scaling parameter introduces a bias that otherwise would not exist. If the CIRSOC recommendation is used, the magnitude of this bias increases with the aspect relation a/b. Fig. 9 illustrates typical Argentinean aspect relations of f/b =0.12 and h/b =0.4. Analysis of this figure reveals a noticeable difference between the loads in the a/b=1 and a/b =3 cases that can be attributed to the aforementioned bias.

[1] The large differences between the BRE results and the UFRGS results in Fig. 7 will be explained later in this section.

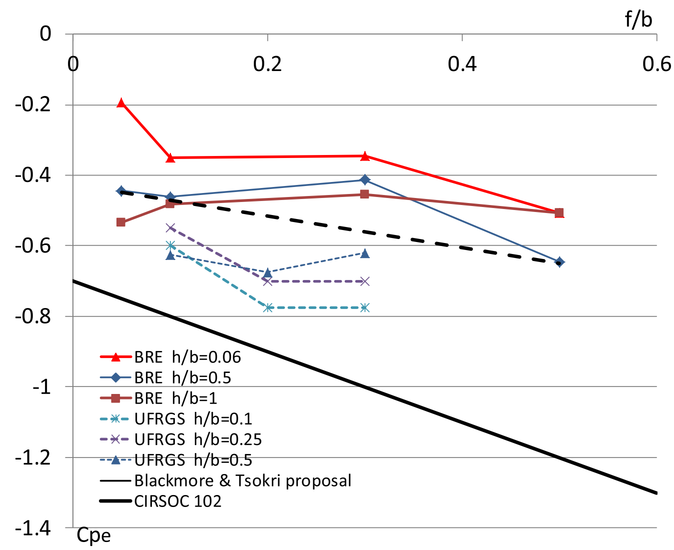

Fig. 5. Loads on the MWFRS under normal-to-eaves wind. Suctions on central zones 'c+d'.

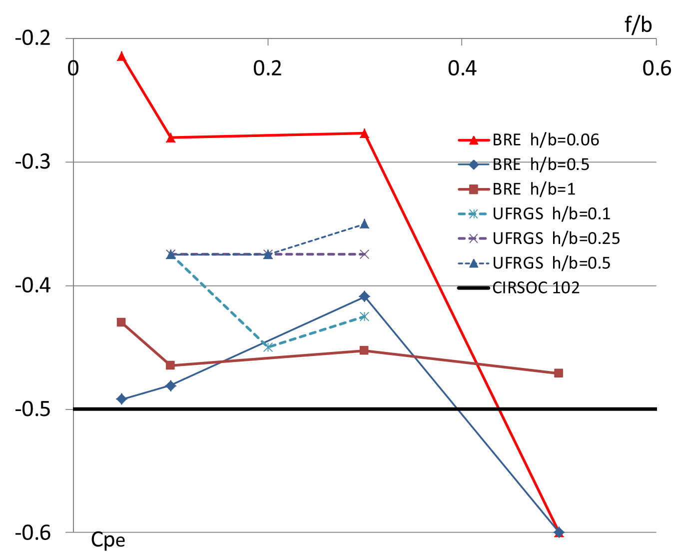

Fig. 6. Loads on the MWFRS under normal-to-eaves wind. Suctions on downwind zones 'e+f'.

The BRE results were reported using an influence area distribution derived from Eurocode. The latter does not use 'a' as a scaling parameter and does not use 'h' to define the influence areas, as defining them introduces a limitation to buildings with spans smaller than twice the ridge height, a condition that makes sense only in the context of loads for duo-pitch planar roofs. Taking into account the fact that for this wind direction the ESG model is not expected to perform optimally, since most of the roof is affected by turbulence generated by the building, a recommendation based on BRE data appears the best option. Fig. 10 and Table 3 summarise this criterion, with Table 3 coefficients included in Fig. 7 in order to illustrate the difference between ESG and ideal model data.

3.3. Loads on components and cladding

Although loads on components and cladding should be based on detailed point pressure fluctuation data, such measurements for curved roofs are scarce, with only Ng (1983) and Wittwer et al. (2004) including them. Fig. 11 compares the mean pressure coefficients and

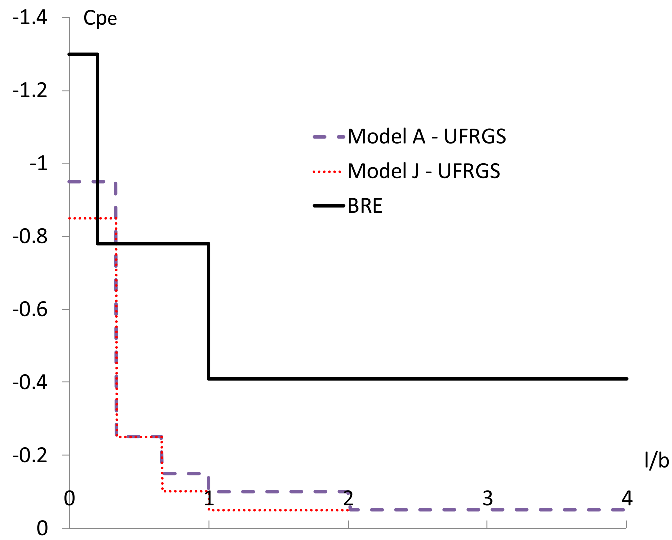

Fig. 7. Load distribution along the roof on the MWFRS with wind parallel to eaves. Results of models A and J tested at UFRGS. Distance along the roof is scaled with the span.

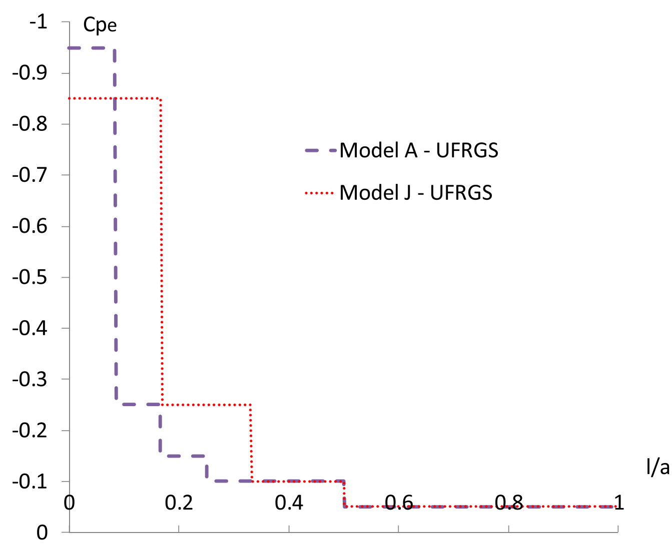

Fig. 8. Load distribution along the roof on the MWFRS with wind parallel to eaves. Results of models A and J tested at UFRGS. Distance along the roof is scaled with the length.

length.

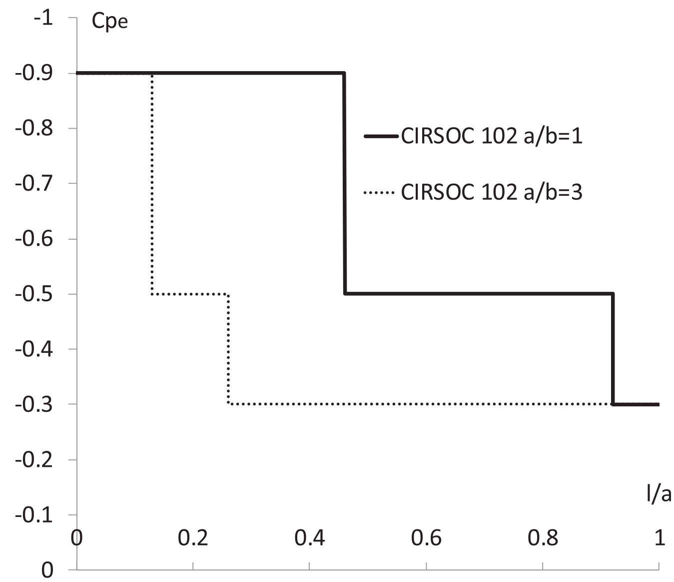

Fig. 9. Load distribution along the roof on the MWFRS with wind parallel to eaves. CIRSOC 102 recommendation for two buildings with f/b=0.12 and h/b=0.4.

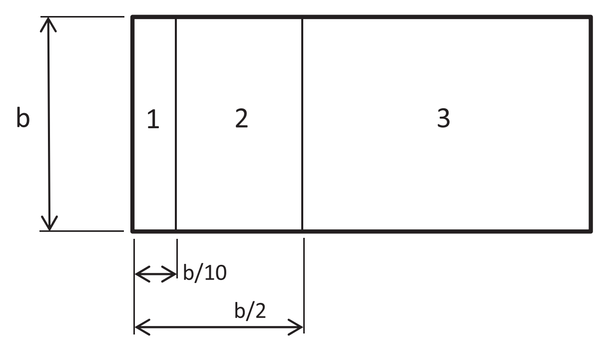

Fig. 10. Proposed recommendation for loads on the MWFRS with wind parallel to eaves. Key to roof zones.

Table 3
Proposed recommendation for loads on the MWFRS with wind parallel to eaves. Load coefficients.

	f/b			
Zone	0.06	0.1	0.3	0.5
1	−1.4	−1.3	−1.1	−1.1
2	−0.8	−0.8	−0.8	−1.0
3	−0.4	−0.4	−0.4	−0.5

pseudo-static coefficients corresponding to minimum peak pressures of 1, 4 and 16 s duration (full-scale equivalent) across the central section of a hangar (Wittwer et al., 2004). These data were obtained via a wind tunnel test with proper wind simulation (suburban area) at Re =10^6 and a normal-to-the-eave wind direction. The aspect relations of the model were f/b =0.1, h/b=0.25, a/b=1 and the roof was smooth, while the pseudo-static coefficients were derived from Cook-Mayne peak coefficients (Cook, 1990). The mean pressure distribution for the same model but with a rough roof surface is also included in the figure, in which it can be seen that the three pseudo-static distributions converge to lower (absolute) values than the mean distributions. The figure also includes the mean coefficients for UFRGS model M (see Table 1), the analysis of which confirms that an assessment based on mean coefficients would overestimate the local loads.

The only other sources of local fluctuating load data are the Ng experiments; unfortunately, the Reynolds numbers in these experiments were between 2.9×10^4 and 9.7×10^4, in other words too low for the extraction of quantitative information. Fig. 12 compares full-scale mean pressure coefficients across the central section of a greenhouse with f/b=0.5 (Hoxey and Richardson, 1984), with similar models tested under identical conditions as in the Ng tests, in the same wind tunnel, at different Re (Johnson et al., 1985). Analysis of this figure reveals that proper modelling of the loads required Re numbers above 1.5×10^5. However, as Ng's model 4 was tested at Re=9.7×10^4, a certain amount of qualitative analysis can still be carried out. Fig. 13 shows contour plots of the largest values (both positive and negative) of point pressure coefficients for wind directions varying every 15 degrees. Since the distributions have two axes of symmetry, four coefficients are plotted in one figure: maximum and minimum mean and pseudo-static coefficients. The aspect relations of the model were f/b=0.27, h/b=0.09 and a/b=1. The roof had circumferential ribbing, a sort of corrugation that showed to be of little aerodynamic influence when compared with an identical model with smooth roof. The pattern of the maximum pressures is similar for mean and pseudo-static coefficients; the highest

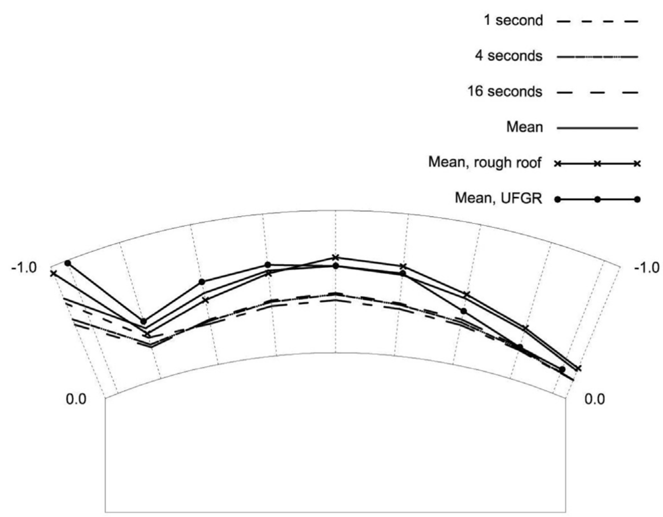

Fig. 11. Pseudo-static and mean point pressure coefficients across the central section of a hangar.

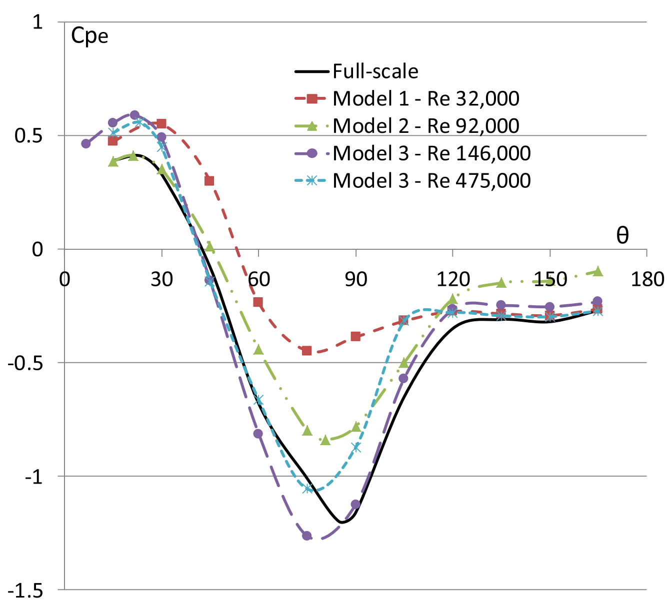

Fig. 12. Comparison of full-scale and UWO model-scale circumferential pressure distributions.

loads occur near the eaves and decrease towards the ridge line. Positive coefficient values are higher if pseudo-static coefficients are considered. Conversely, the highest pseudo-static suctions are less severe than their mean counterparts, although the mean and pseudo-static suction coefficient patterns are roughly similar, with the highest suctions occurring near the facades and decreasing towards the centre of the roof. Even though the values of the coefficients displayed in Fig. 13 cannot be considered for codification purposes, they provide an indication that the zoning criterion currently in use in codes of practice needs further revision.

For components and cladding, CIRSOC 102 specifies:

- ‘I. At roof perimeter, use the external pressure coefficients in Fig. 5B with θ based on spring-line slope’
- ‘II. For remaining roof areas, use external pressure coefficients of Table 8 multiplied by 0.87.’

The values of the code shown in Fig. 5B correspond to state-of-the-art pseudo-static coefficients for duo-pitch roofs. Recommendation I is thus an acceptable approximation until new state-of-the-art pressure

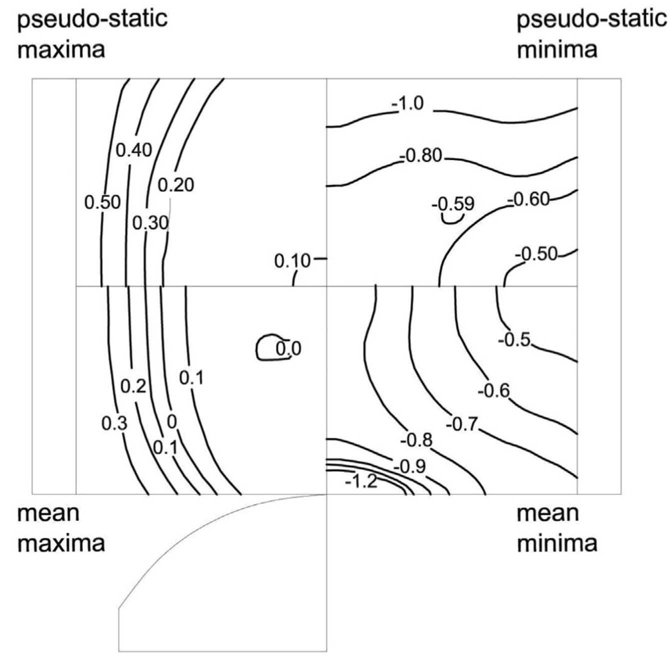

Fig. 13. Contour plots of worst-case point pressure for incoming wind directions varying every 15°.

fluctuation information is produced, even though the zoning proposed by CIRSOC 102 is not in full agreement with that arising from Fig. 13.

Recommendation II refers to Table 8 of the code, which provides the values for the MWFRS that appear in Figs. 3–6 plotted using black continuous lines. It was argued in Section 3.1 that these values do not properly represent the global loads, hence it also cannot be expected they better represent the local loads. Blessmann's reports instead provide mean local coefficients that can be used to produce a recommendation, that being ESG model-based, would err on the side of safety, at least for suctions.

4. Summary and future work

In this paper, a review of wind loads on cladded buildings with vaulted roofs was presented and the available information compared to the CIRSOC 102 treatment, a code whose recommendations are based on studies published in 1914. In general, the code treatment is not in agreement with current experimental evidence, although existing information regarding this particular typology is both limited and small in absolute terms. Potential criteria and values with which to update the code were discussed. However, it should be recognised that it is also necessary to improve our knowledge of these factors in order to design safer and more cost-effective structures.

In particular, future research should focus on the following issues: a) load coefficients for f/b lower than 0.1; b) load coefficients for f/b between 0.1 and 0.3; c) load coefficients for h/b lower than 0.5; d) local load coefficients; and e) full-scale measurements with which to validate model data.

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