Turbulent Wind Loads on Arch-Roof Structures: A Review of Model and Full-Scale Results, and the Effect of Reynolds Number

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ABSTRACT

Design data for wind loads on arch-roof structures tested in representatively-scaled atmospheric flows are sparse in the literature. This situation is exacerbated by the potential Reynolds number sensitivity of these rounded structures.

An extensive data base, derived in a boundary layer wind tunnel by the third author at relatively low Reynolds numbers, is summarized in this paper. Many critical design load cases originated from quartering wind directions which are not likely to be very Reynolds number sensitive; however, for winds normal to the ridge, early separation resulted in large unbalanced loads which do not apparently correlate with full-scale structural experience.

Further experiments by the first two authors have indicated a strong Reynolds number dependence for winds normal to the ridge, resulting in lower unbalanced loads at higher Reynolds numbers. Although even here, the maximum Reynolds number obtainable falls short of full scale, the results agree fairly well with the limited full-scale data available. It is suggested that these results could form the basis for correction of the low Reynolds number results to full-scale design loads. This work is continuing.

INTRODUCTION

Arch-roof structures represent a form that has widespread application, particularly in farming. Since they are often of very low dead weight, wind loads represent a significant design problem, particularly in warm climates where snow loads do not dominate.

Although wind tunnel tests have proven to yield valid results for sharp-edged structures when compared to full-scale measurements (for example, Dalgliesh, 1975; Vickery, Surry and Davenport, 1984), tests on rounded structures have difficulties in reproducing full-scale measurements due to their sensitivity to the Reynolds number. The latter is defined as $Re = Ud/\nu$,

where U is the mean wind speed at a local reference height

d is a representative dimension

and ν is the kinematic viscosity of the working fluid; usually air for most structural applications.

Since Reynolds numbers for full-scale arch-roof structures are of the order of 10^7, they are almost impossible to attain in model-scale studies. Experience with vertical circular-cylindrical structures (Basu, 1982) indicates that there is a strong dependence of their aerodynamic behaviour on Reynolds number over the range covering most model studies and full-scale, i.e. from about 10^4 to 10^8. There are two primary reasons for this. The first is the position of the flow separation point, which is dependent on the surface boundary layer state and hence the Reynolds number. The second is the strength of the vortex shedding which affects the magnitude of the wake suctions and is also dependent on the Reynolds number, presumably through the position of the shear layer separation. There is little comparable information for the horizontal half-cylinder on a surface, although there is for cylinders tested with splitter plates. These show vortex shedding to be inhibited which would be expected to reduce the Reynolds number sensitivity of the wake suctions. Arch-roof shapes might also be expected to have reduced Reynolds number sensitivities in actual practice because of their three-dimensionality and the complex boundary layer flow field in which they are immersed. Nevertheless, because the separation point is not fixed, some Reynolds number sensitivity would still be expected.

This paper presents some on-going work at The University of Western Ontario, on arch-roof structures, with particular emphasis on an investigation of Reynolds number sensitivities.

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HISTORICAL LOADING MODELS FOR ARCH-ROOF STRUCTURES

The first tentative loading model for rounded roofs was proposed by Albert Smith in 1914 (Ng, 1983), presumably based on wind tunnel tests in flows lacking adequate atmospheric simulation. This model was discussed and compared by an ASCE Sub-committee (see ASCE reference, 1936) with a model proposed by the Standard Committee of the U.S.S.R. in 1924-25 (see Figure 1). In the case of arch roofs with no side walls, it was reported that the suctions in the leeward region were substantially the same for a range of rise/span ratios 'r', while poor agreement existed in the windward quadrant. The design mean pressure coefficients used in Smith's model are described by the following equations:

i) Windward Quarter $(\theta/2\,\theta_0 < 0.25) : C_p = 1.4\,r$

ii) Central Half $(0.25 < \theta/2\,\theta_0 < 0.75) : C_p = -r - 0.7$

iii) Leeward Quarter $(\theta/2\,\theta_0 > 0.75) : C_p = -0.5$

where θ_0 is the half-angle subtended by the roof - i.e. a semi-cylindrical roof has $\theta_0 = 90°$.

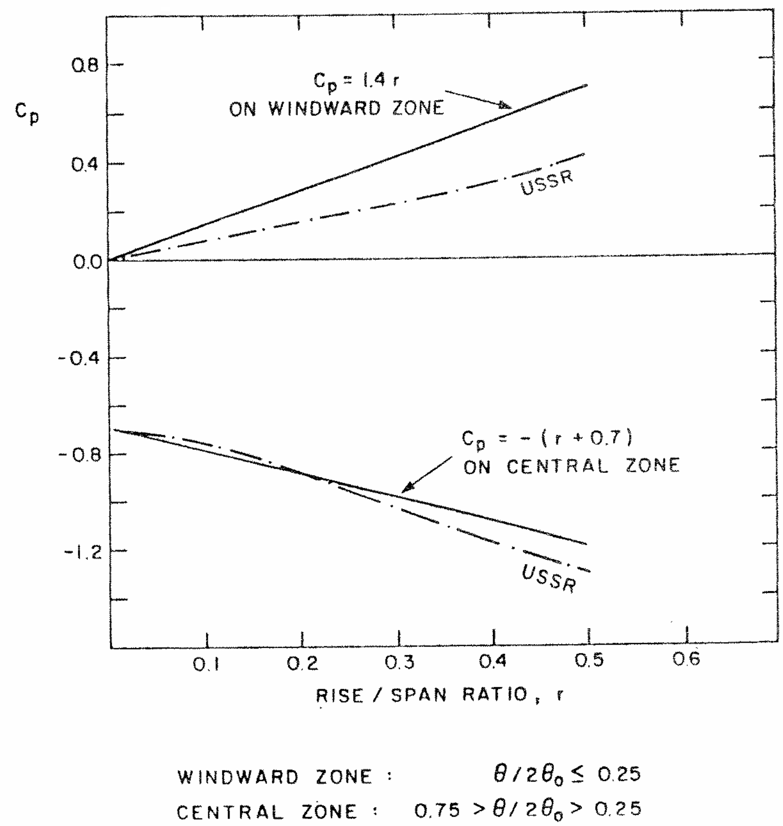

FIG. 1 The Loading Model For Arch-Roofs (No Sidewalls) Proposed in the Thirties

This loading model is still in use by many current building codes with little or no revision; for example, the recommendations in the American National Standards Institute (ANSI, 1982) and the American Society of Civil Engineers (ASCE, 1961) are similar to the above.

The above equations are attractive in their simplicity; however, they have not been verified, either by modern boundary layer wind tunnel techniques, or, more importantly, by comparison with high Reynolds number results either from model tests or in full scale. As well, the above equations do not provide separate detailed local loading information, nor do they provide any insight into the unsteady loads; they simply assume conventional gust factors.

W.K. NG'S STUDY ON ARCH-ROOF STRUCTURES

An extensive testing program on arch-roof structures was carried out by the third author (Ng, 1983) who studied local and spatially-averaged external mean and unsteady wind pressures, and internal pressures, on various models with different rise/span ratios. As well, the effect of changes in geometry, such as adding side walls or circumferential ribbing to the arch, and the sensitivity of the measured pressures to changes in exposure were observed.

In particular, five models were studied under the influence of open country and suburban boundary layer exposures (see Table 1). The models had rise/span ratios ranging from 0.27 to 0.5, with all five of the models being instrumented for local and spatially-averaged external pressure measurement and three of the models also being equipped for the measurement of internal pressures. All of the models had circumferential corrugations except for one of the external pressure models, which was used to verify that the corrugations were of little aerodynamic importance. Some of the models were also tested in the presence of dummy length extensions.

TABLE 1

PARAMETERS OF THE FIVE MODELS TESTED BY NG

Model Series		**0**	**1**	**2**	**3**	**4**
Length	(m)*	9.5	15.2	22.9	31.7	31.7
Span	(m)	9.5	15.2	22.9	31.7	31.7
Rise/Span		0.5	0.37	0.31	0.27	0.27
Radius	(m)	4.7	7.9	12.7	19.1	19.1
Door Size	(m)	-	5.6x3.2	6.3x3.2	-	19.1x2.5
Corrugation 'Depth/Pitch'	(m)	0.2/0.6	0.2/0.6	0.2/0.6	smooth roof	0.2/0.6
Side-Wall (optional)	(m)	-	3	3	-	3
Leakage**	(%)	-	0.4	-	-	-
Subtended Angle ($2\theta_0$)		180°	146°	126°	114°	114°

* The dimensions were based on information provided by Fairford Industries Ltd. as representative full-scale values. Models were built at a scale of 1:100.

** Leakage is given as % of the surface area of the end wall.

Ng presented tentative loading models for two classifications of structure and for two classifications of loads. The structures were classified as:

Group I $0.20 < r < 0.35$
Group II $0.35 < r < 0.60$

The two classifications of loads were for local loads, shown in Figure 2 and for overall structural loads, shown in Figure 3. In all cases, loads are specified as $p = q\, C_e\, C_g\, C_p$ where p is the design pressure, q is the reference dynamic pressure usually taken at a height of 10m in open country, C_e is a factor that essentially corrects q to the value at ridge height and the term $C_g\, C_p$ (the product of the gust factor and mean pressure coefficient) is the peak pressure coefficient which has been measured directly in the experiments. In Canadian practice, q refers to mean hourly dynamic pressures. If a fastest mile reference dynamic pressure is used, the peak coefficients should be reduced accordingly; a factor of 1.66 is representative - i.e. Canadian $(C_g\, C_p) \simeq 1.66$ American $(C_g\, C_p)$. Furthermore, q and C_e should be taken for an open country exposure, as the peak loads have been found to vary very little with exposure. Rougher exposures dramatically reduce mean loads but have little effect on the peaks.

The loading models shown in Figures 2 and 3 were derived from the peak values obtained in the wind tunnel tests together with appropriate reduction factors. Note that in Figure 3, for uplift forces, the specified values for $C_g\, C_p$ have been defined such that, for a structure of given L/H, the indicated value of $C_g\, C_p$ must be applied uniformly over the entire roof surface to recover the appropriate uplift. Also note that the loads suggested in Figures 2 and 3 over the central part of the arch are modest. The higher loads near the ends in both cases are associated with quartering winds. Although Ng included higher suggested suctions over the central part of the arch that might be associated with higher Re, these values must be considered tentative and subject to revision in light of better data.

Ng made comparisons with currently accepted design values and found that the latter apparently overestimate the local loads, as well as the primary structural loads in the windward and leeward quarters. As far as the central region is concerned, Ng's suggested values for structural loading are also smaller than the current design values, but no firm conclusion could be made here because of the uncertainty in the Reynolds number scaling of the tests, and its potential importance in this region.

In reviewing Ng's suggested loads, it is important to note that many of the critical loading cases actually occurred for quartering winds or winds along the ridge. This is particularly true of the local loads.

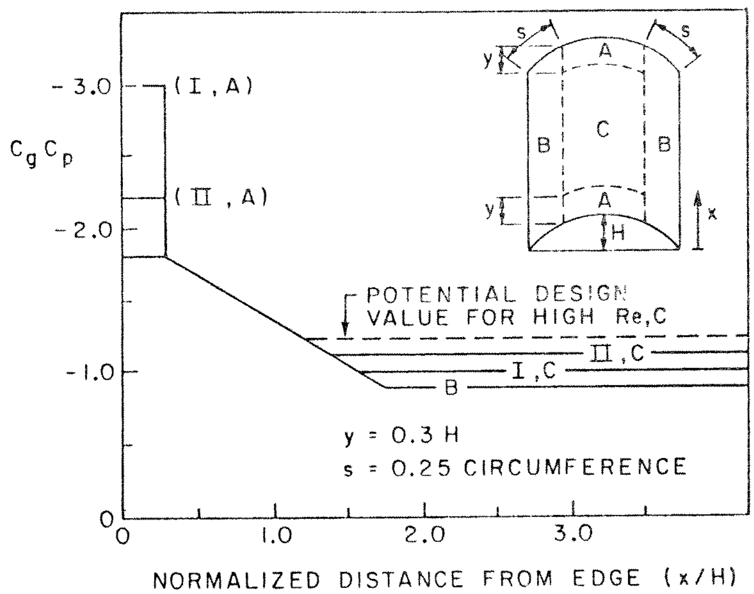

FIG. 2 Ng's Tentative Model for Local Loads (Subject to revision - see text)

Thus the Reynolds number sensitivity for the broadside wind direction is not as crucial as it first appears; however, the lower Reynolds number results do tend to suggest relatively large wake suctions and low ridge suctions for broadside winds and this leads to more unbalanced loads than for higher Reynolds number data, despite the latter having higher suctions near the ridge.

Internal pressures are beyond the scope of this paper, but were analysed by Ng and were found to be generally negative unless a dominant opening existed on the windward wall.

The opportunity to continue Ng's work, and to at least partially resolve the extent of the Reynolds number effect and to attempt to model pressures closer to those of full-scale, was made available through a more recent study of tent structures, arch roofs and domed roofs (Johnson and Surry, 1985).

U.W.O. STUDY ON ARCH ROOF REYNOLDS NUMBER DEPENDENCE

Three semi-cylindrical models of increasing size were tested in the Boundary Layer Wind Tunnels I and II (BLWT I and II) at a number of speeds to provide overlapping Reynolds numbers between models. The smallest model was one that Ng used in his study. Both of the larger models were smooth-surfaced without corrugations. All of the models, except the medium sized one, were tested or retested in BLWT II. The models were tested only for broadside wind directions within coarsely modelled upstream terrain to simulate an open country exposure. Mean, peak and rms pressure coefficients were measured at each speed; however, at low speeds much of the peak data was contaminated with electronic and acoustical noise. The pressure coefficients were initially measured with respect to the free stream wind speed and then converted to be referenced to the dynamic pressure at the top of each arch roof. This paper presents only the mean pressure coefficients. These were found not to have a strong dependence on the simulated mean profile although some residual dependence on the turbulence characteristics was noted (Johnson and Surry, 1985).

The mean C_p results from the tests are shown in Figure 4 for selected overlapping Reynolds numbers. There appears to be a definite Reynolds number trend, with peak suctions steadily increasing through 150,000, and then decreasing somewhat. It is not clear whether this latter decrease is significant. Further experimental verification is required. The windward pressures and wake suctions are remarkably constant, with the exception of the results for 90,000; again, this needs verification as to its validity. The appropriateness of the higher Reynolds number results for application to design can be determined through comparison of the U.W.O. results with full-scale measurements.

FULL-SCALE STUDIES ON ARCH ROOFS

Full-scale results provide "truth data" at realistic Reynolds Numbers, subject to the many constraints under which full scale experimentation takes place. In fact, full-scale data on arch-roof structures are sparse. Those found were from the Akron Airship Dock (Arnstein and Klemperer, 1936), an inflatable structure in France (Grillaud, 1981) and a plastic film greenhouse in England (Hoxey and Richardson, 1983). Space does not allow each experiment to be detailed here, but it is noteworthy that, in the airship dock study, there was some difficulty with the reference static pressure used and the shape was not a perfect arch; in the inflatable structure study, both mean and unsteady measurements were taken, and the site was surrounded by a number of low but not insignificant buildings; in the plastic-film greenhouse study, a number of structures were built specifically as test objects, one of which was a true semi-cylindrical greenhouse in an open country exposure. Some further details are also given in Table 2. The mean pressure distributions along the mid-section of these structures for a cross-wind are shown in Figure 5, with the highest Reynolds number U.W.O. measurements included for reference.

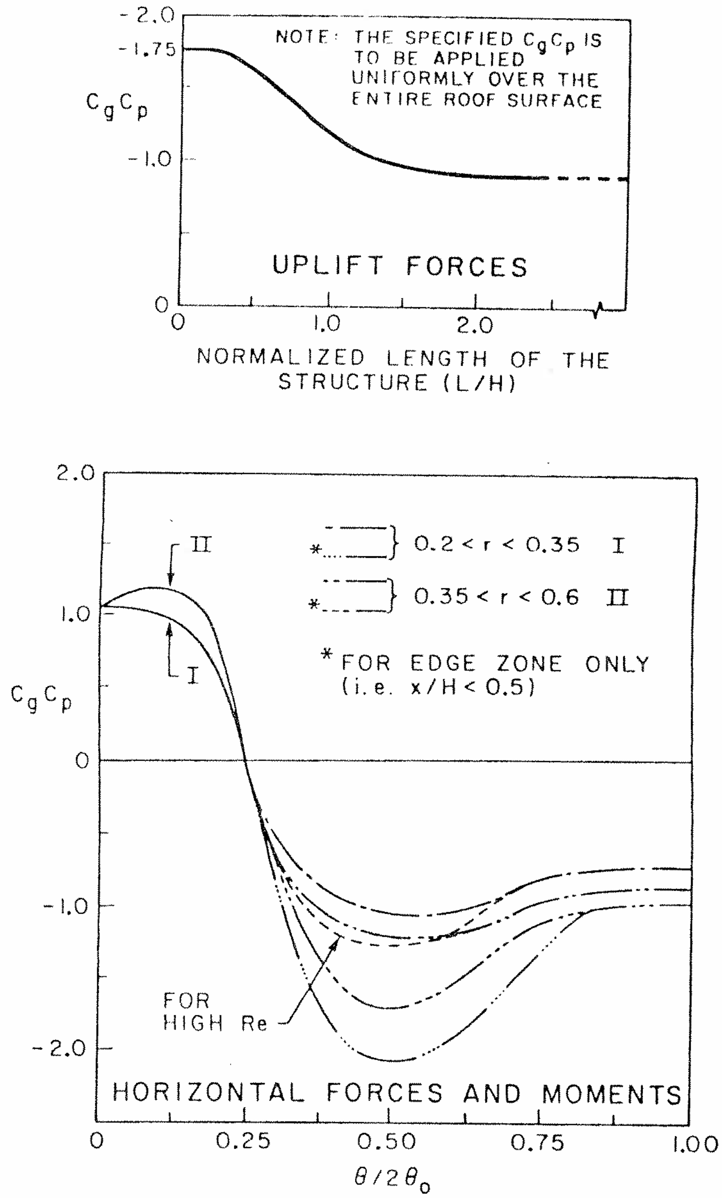

FIG. 3 Ng's Tentative Model For Overall Structural Loads (Subject to revision - see text)

Apart from the Akron airship dock data, whose absolute ordinates depend on the assumed internal pressure, the agreement is remarkably good, particularly for the wake suctions. This is further illustrated by comparing two parameters of the pressure distributions; namely, the position of the separation point (where the essentially-constant wake pressure begins) and the ratio of largest mean suction to the average wake suction. Both of these quantities can be derived independently of the definition of reference speeds and hence magnitudes of the coefficients, although they are affected by offsets in the C_p's as evident in the Akron case. These results are shown In Table 2 and again illustrate the good agreement between the model data at the higher Reynolds numbers and the more reliable of the full scale results.

These mean coefficient comparisons suggest that Ng's loading model of Figure 3 may reduce to simply extending those curves initially suggested for the edge zones to the entire structure; however, a final recommendation for these C_gC_p values must await analysis of the unsteady loads. Similar increases may also be required for local loads in region C of Figure 2.

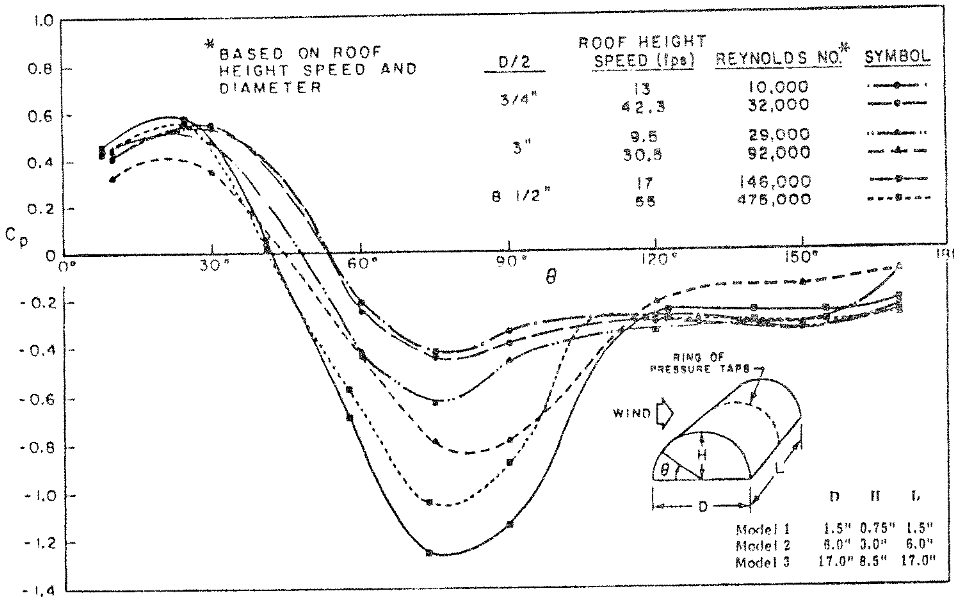

FIG. 4 Circumferential Pressure Distributions on Arch-Roof Models at Various Reynolds Numbers

TABLE 2
COMPARISON OF PARAMETERS OF FULL-SCALE AND MODEL STUDIES

Source of Information	Rise/Span	Shapes of Both Ends	Position of the Flow Separation	P_{max} Suction / P_{rear} Suction
Airship Dock	0.61	Spherical	~90°	1.6
Inflatable Structure	0.5	Spherical	~115°	5.0
Greenhouse	0.5	Sharp Edge	~110°	4.1
Ng's Low Re Data	0.5	Sharp Edge	~90°	1.2
U.W.O. High Re Data	0.5	Sharp Edge	~110°	3.5 to 5.2

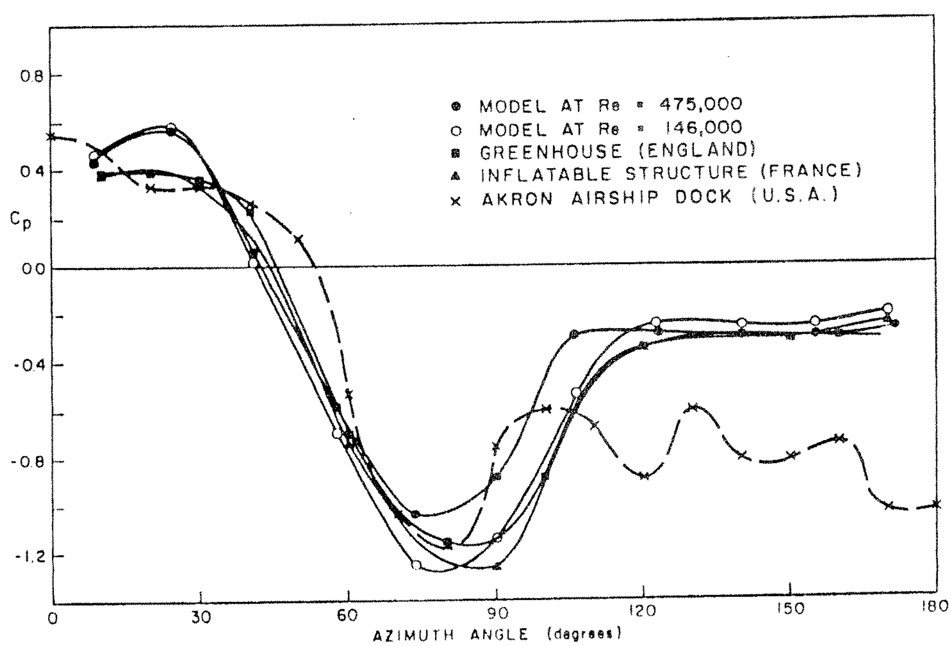

FIG. 5 Comparison of Full-Scale and High Re Model-Scale Circumferential Pressure Distributions

CONCLUDING REMARKS

The present study has shown a strong Reynolds number dependency for model-scale arch roof structures in cross-winds. The highest Reynolds number wind tunnel results compare well with the most reliable full-scale results. These high Reynolds number results provide a tentative basis on which to correct the results of Ng's broad parameter study to approximate full-scale conditions. Such revised recommendations for design loads will be included as part of Johnson and Surry, 1985.

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