Computational Modelling of Wind Loads on Three Dimensional Walls

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1. Introduction

Considerable research interest has developed recently over the determination of wind loads on one of the simplest of structures - free standing walls. Following detailed wind tunnel measurements in the UK and Australia [1] 10 years ago, new wind loading data for free standing walls appeared in many major design standards. Concerns over these standards led to new full-scale parametric research being initiated at the Silsoe Research Institute by the Building Research Establishment. This research has been augmented by computational fluid dynamic (CFD) studies at Auckland University and by further wind-tunnel studies at Oxford University. Earlier work on computational modelling of the wind loads on two-dimensional free standing walls [2] using the finite volume package PHOENICS and the standard k-ε turbulence model had shown reasonable agreement with the available full-scale data. However more recent three-dimensional computational studies [3] using similar techniques showed that while the computational and experimental results are in reasonable agreement for a wind perpendicular to a wall, the CFD solutions fail to correctly model the very high loads which exist near the windward end of a finite wall for a glancing wind.

Although the structure of a free standing wall may be very simple the flow patterns around that wall for a glancing wind can be very complex. Fig. 1 illustrates the velocity vector maps in a horizontal and vertical plane near the windward end of a 9h long (h = wall height), 0.1h thick wall for a 130° wind direction (40° from perpendicular). It is possible to discern flow features which include ground separation windward of the wall and recirculating flows in both the vertical and horizontal planes leeward of the wall. It is almost certainly the failure of the CFD solution to correctly model these three-dimensional flows which results in poor wind load prediction.

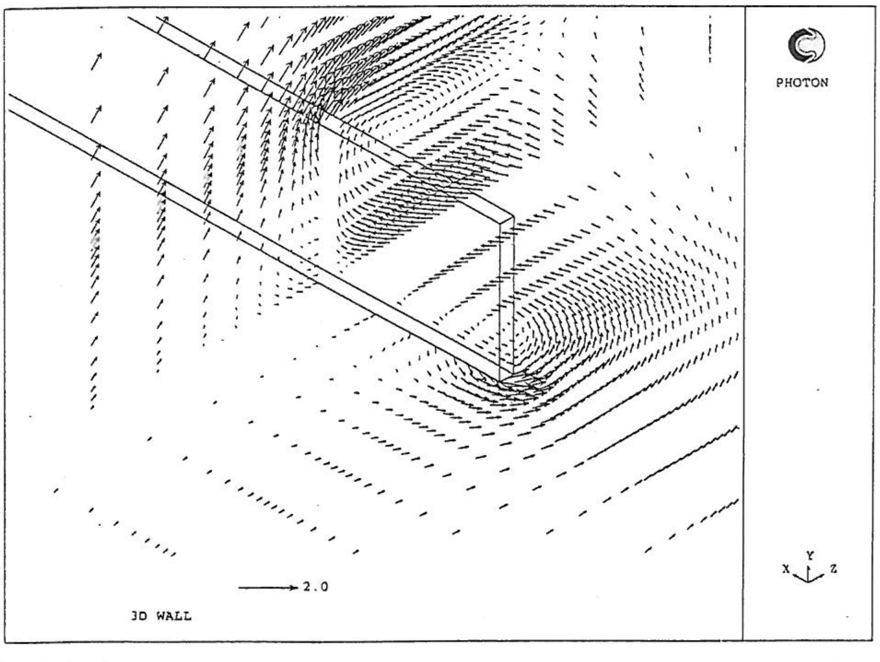

Fig. 1. Velocity vector maps in a horizontal and vertical plane near the windward end of a finite wall. Wind direction 130°.

The deficiencies of the previous modelling is illustrated in Fig. 2 which shows a comparison of the mean force coefficient for the first three zones at the windward end of a 9h long wall for various wind directions. Although both the experimental and computational results have a similar form it is clear that the maximum load on the windward zone (0-h) is significantly under-predicted and that the maxima of the CFD results occur too near perpendicular.

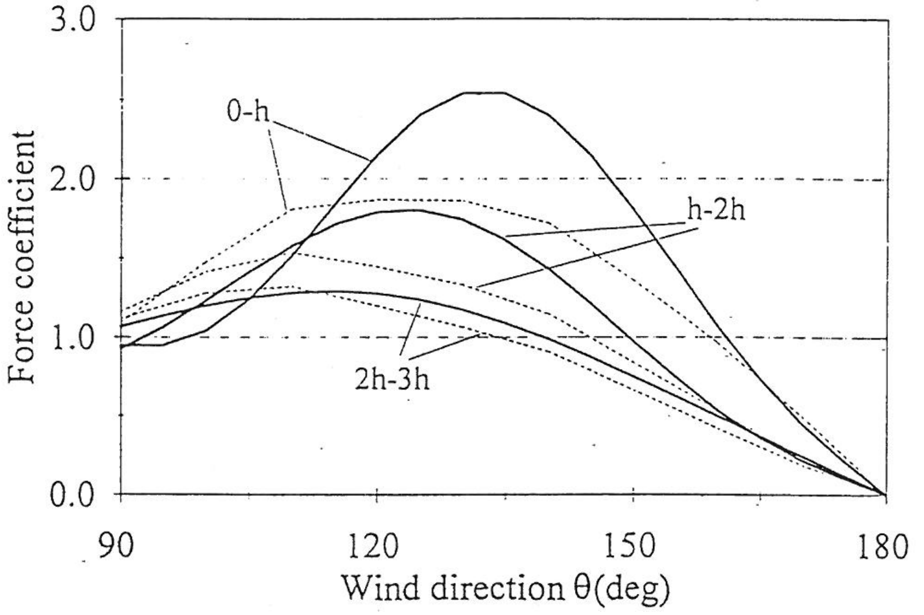

Fig. 2 Comparison of mean force coefficient for first 3 zones at the windward end of a 9h long wall (solid lines, full-scale; dashed lines, CFD). From reference 1.

2. The k-ε turbulence model

Examination of the CFD data tended to suggest that the deficiencies may be associated with the well known tendency of the k-ε turbulence model to produce results which exhibit a reluctance to separate from surfaces and to produce very high negative pressures near a corner which subsequently decrease in magnitude more rapidly than experimental results suggest is correct. Murakami [4] discussed this phenomena while comparing k-ε, ASM and LES turbulence models at the first Computational Wind Engineering Conference and has pursued a solution to the problem by proposing the MMK model as presented at the second CWE conference [5]. Although the MMK model appears to have the correct effect in some situations it did not appear to have a significant effect when applied to the three-dimensional wall problem by this author.

It is the author's opinion that the fundamental flaw with the k-ε turbulence model lies in the calculation of the Reynolds stresses tensor τ_{ij} directly from the local mean strain-rate tensor S_{ij} by using

$$\tau_{ij} = -\rho\overline{u_i u_j} = 2\mu_t S_{ij} - \frac{2}{3}\rho k \delta_{ij} . \qquad (1)$$

where $$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \qquad (2)$$

and $$\mu_t = C_\mu \rho k^2 / \varepsilon \qquad (3)$$

This calculation produces sensible results provided the strain-rate is not changing too rapidly and hence the turbulence is able to adjust in such a manner that the Reynolds stresses reflect the strain-rate. The anisotropic component of the Reynolds stress tensor may be viewed as an a non-uniform distribution of the turbulence vorticity vectors which is brought about by the mean strain-rates. However if the strain-rate is changing rapidly then the Reynolds stresses are unable to instantaneous adjust to the change and will respond to the change in a transient manner. One example of a flow where the strain-rates are changing rapidly is the flow over the windward eaves of a house or a two-dimensional rib. Murakami [4,5] has shown that in this vicinity the standard k-ε model tends to predict much higher levels of turbulence than are measured in experimental studies. It is the author's opinion that this occurs because the standard model assumes that as the flow passes from the low strain region upstream into the high strain region around the eaves the Reynolds stresses change in proportion to the strain-rates, whereas in reality the Reynolds stresses remain at a much lower level.

3. The k-ε-T turbulence model

In an attempt to develop a turbulence model which responds to changes in mean strain-rate in a more realistic manner, addition conservation equations were solved of the form

$$\frac{D\zeta_{ij}}{Dt} = \frac{1}{T}\left(S_{ij} - \zeta_{ij}\right) \tag{4}$$

where ζ_{ij} is the effective strain-rate tensor and T is the time constant of the response which was calculated from

$$T = C_T \frac{k}{\varepsilon} \tag{5}$$

with the constant $C_T = 0.3375$. The effective strain-rate tensor then replaced the strain-rate tensor in equation 1.

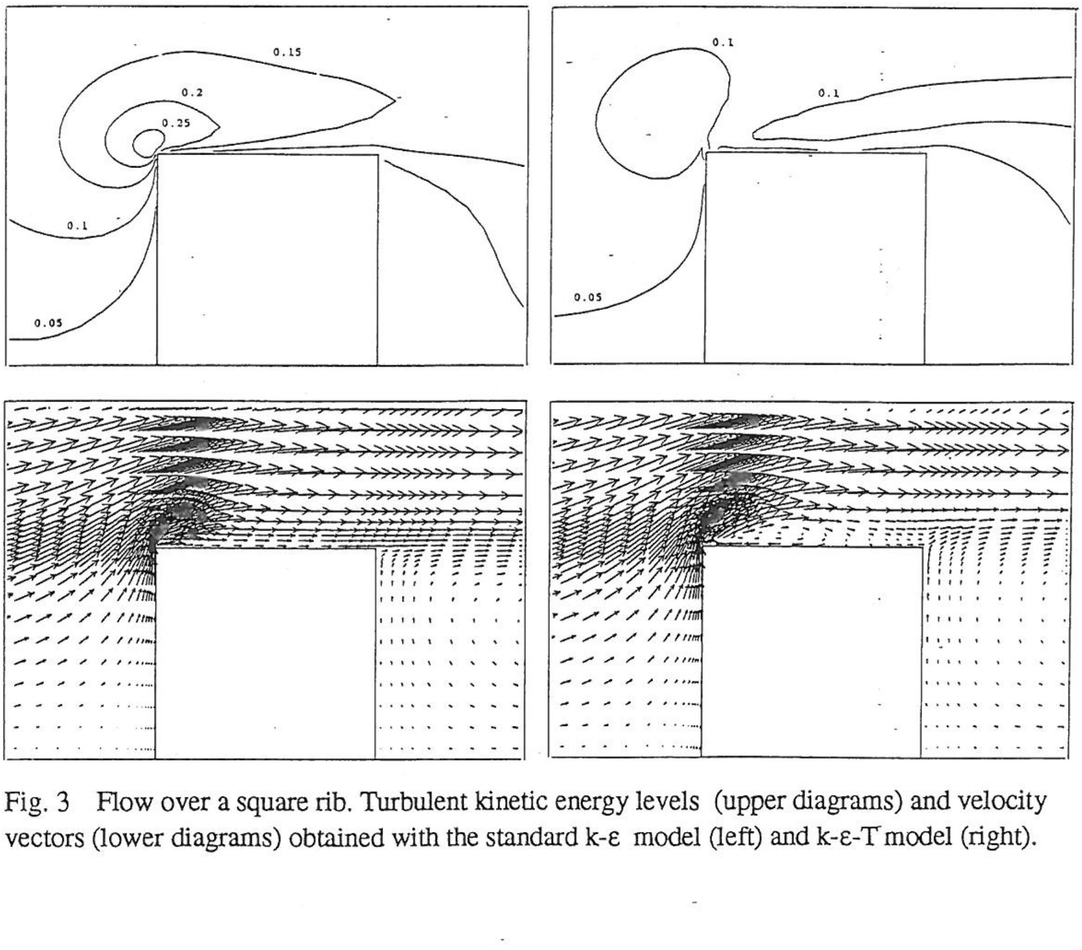

Fig. 3 Flow over a square rib. Turbulent kinetic energy levels (upper diagrams) and velocity vectors (lower diagrams) obtained with the standard k-ε model (left) and k-ε-T model (right).

Initially this model was applied to the two-dimensional flow over a square rib and as illustrated in Fig. 3 it was found that with the k-ε-T model the turbulence around the windward eaves was significantly reduced and the flow separated and reattached in a more realistic manner.

The k-ε-T model was then applied to the three-dimensional wall problem discussed earlier where it was found that the new turbulence model did modify the pressure distribution on the leeward side of the wall. Although these changes, as illustrated by comparing Fig. 4 with Fig.2, do show an improvement in the modelling there are still significant differences.

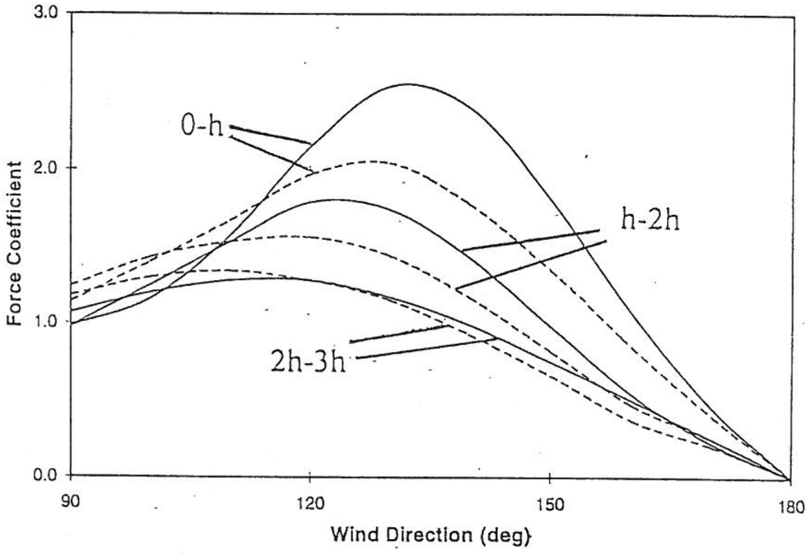

Fig. 4 Comparison of mean force coefficient for first 3 zones at the windward end of a 9h long wall (solid lines, full-scale; dashed lines, CFD-k-ε-T turbulence model).

4. Conclusions

Although the structure of a free standing wall is very simple the flow around it is complex. Previous attempts to model this flow using the standard k-ε model have shown significant deficiencies. In an attempt to improve the modelling a transient k-ε-T model has been developed. This model shows significant improvement in modelling the flow over a square rib but only slight improvement in modelling the flow around a wall.

References

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