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Generalization of wind-induced interference effects for two buildings

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Abstract. Wind-induced interference effects on a building are the result of one or more adjacent buildings modifying the flow of wind around it, which may result in a significant increase or decrease in wind loads on the building. Wind loading standards and codes of practice offer little guidance to the designer for assessing the effects of interference. Experimental results on interference effects indicate that code recommendations may be significantly low (unsafe) or uneconomically conservative. The paper presents results of an extensive experimental program to study the wind flow mechanisms and to quantify the extent of wind load modifications on buildings due to interference effects. These results have been simplified and presented from the point-of-view of design and codification for the case of two buildings. Based on these results, general guidelines and limiting conditions defining wind interference are formulated and discussed.

Key words: buildings; design; interference effects; shielding; wind loads; wind tunnel experiments.

1. Introduction

In the case of wind flow around an isolated building, the windward walls are subjected to positive pressure due to the direct impact of wind; negative pressure (suction) is generated on the other three walls and roof due to separation of flow around the edges of the building. With the inclusion of another building in the vicinity, the loading pattern becomes quite complex. The buildings may experience enhanced or reduced wind loads depending upon the building geometries, their relative locations, wind direction and upstream terrain conditions. This effect known as wind interference can increase wind loading on a building by up to 80% (Khanduri *et al*. 1998b). Therefore, the effect of adjacent structures on wind loads should be evaluated properly for realistic wind load design of buildings.

Fig. 1 shows a typical example of interference effects causing shielding, i.e., reduction of the drag coefficient acting on a building in the presence of an adjacent building directly upstream. The Australian

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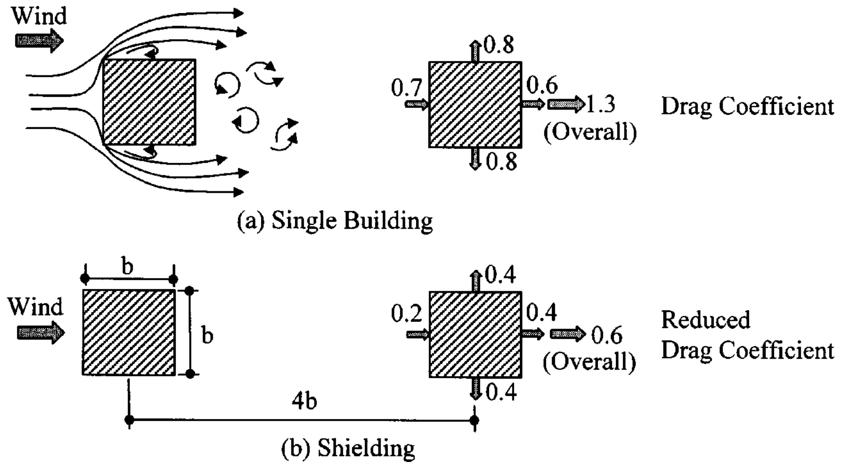

Fig. 1 Modification of wind loads due to adjacent buildings

Standard – SAA Loading Code (SAA 1989) and the Eurocode (1995) refer explicitly to the wind-induced interference effects on the wind loading of buildings. The former provides for a "shielding modifier" based on the wind loading of buildings and a conservative generalization to accommodate the effects of total and local wind loads but it does not address cases for which wind loads may actually increase due to interference; the latter provides very few specific cases of two-building interaction with no traces of any possible generalization. Therefore, there is a lack of guidance to building designers regarding interference effects for structural design.

The paper reports on an extensive study undertaken in order to provide the necessary data to produce some quantitative guidance in this regard. Details have been provided in Khanduri (1997). It should be understood that a complex case of interaction would clearly require wind tunnel tests. Nevertheless, the results presented in this paper will provide a useful compendium of a variety of cases to the building designer, relevant to the interaction of two buildings.

2. Experimental setup

An extensive experimental program was developed to quantify interference effects. Wind tunnel experiments have been conducted to find the mean and fluctuating forces on a building due to an adjacent building of small, medium and large sizes, for several wind directions and various upstream exposure conditions. Fig. 2 shows the different building models used in the study. The experiments involve two rigid, prismatic building models of various sizes, one serving as the instrumented "principal" test model and the other as the mobile "interfering" building model that is used to provide interference by locating it at specific positions upstream or downstream of the principal building. Force or pressure measurements are made on the instrumented model with the interfering model nearby. These measurements are also made on the principal model in isolated condition to facilitate a direct indication of the effect of the interfering building. Typical dimensions of the models have been selected to be representative of real buildings at a geometric scale of 1 : 400. Measurements are carried out to examine the mean and fluctuating aerodynamic forces acting on these models representing typical shapes of small, intermediate and large sized buildings in various arrangements. The principal building consists of a Plexiglas model fitted with 12 pressure taps

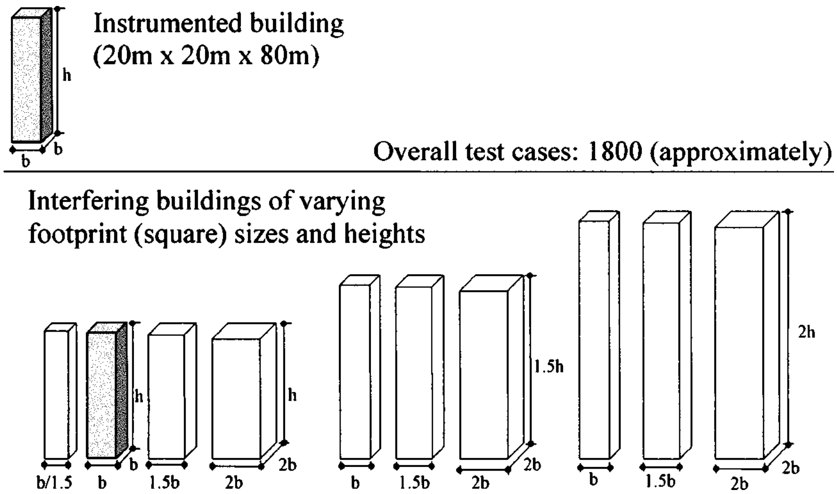

Fig. 2 Building configurations tested in the wind tunnel

uniformly distributed on each of its four faces and the models providing interference are made of wood. Pressure measurements are carried out by using pressure transducers and *pneumatic* averaging (Surry and Stathopoulos 1978) is used to measure the fluctuating pressures in addition to the mean pressures. A pneumatically-averaged signal provides an instantaneous sum of the pressures at a number of tappings on a model surface, thus representing area-averaged pressure whose

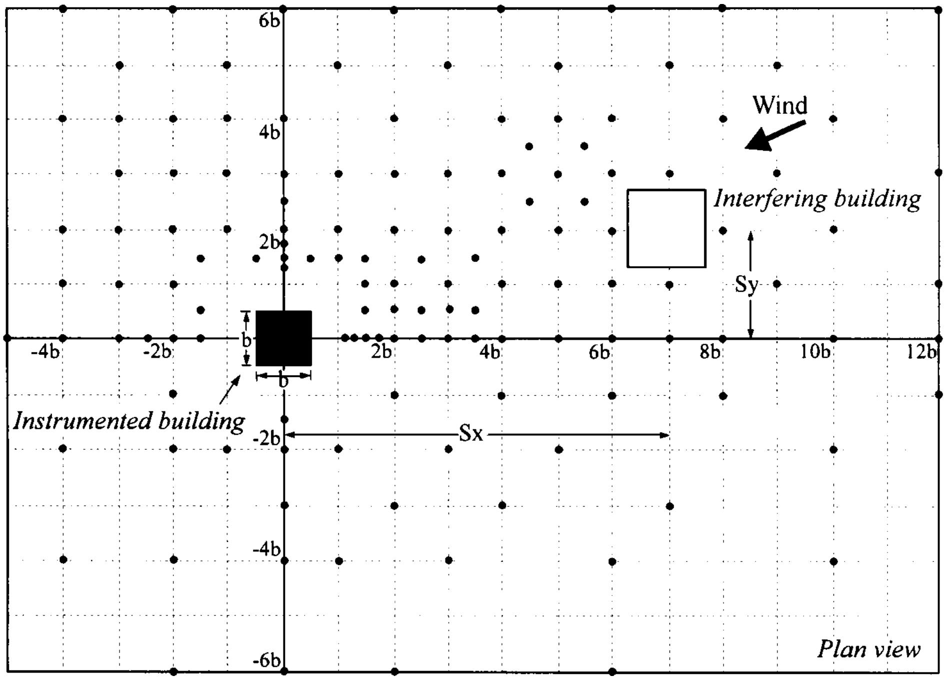

Fig. 3 Experimental plan indicating the different locations of the interfering buildings tested in the wind tunnel

statistics can be investigated. It also makes an efficient use of the wind tunnel, instrumentation and computer resources. The digitization of pressure signals and analysis of the data is done by a waveform analyzer. The aerodynamic forces are measured in terms of non-dimensional along-wind drag and across-wind lift coefficients, for various wind directions and approach terrains. Fig. 3 shows the detailed experimental plan indicating the different locations of the interfering building tested in the wind tunnel. The database generated from experiments is analyzed to create simple and generalized sets of guidelines on interference effects along with the development of empirical models.

3. Results and discussion

Interference effects are presented in the form of non-dimensional Interference Factors (*IF*) that represent the aerodynamic forces on a building with interference from an adjacent building, relative to the forces on a single freestanding building. *IF* can be expressed as,

$$IF = \frac{\text{Force coefficient on principal building (interfering building(s) present)}}{\text{Force coefficient on principal building (isolated condition)}} \tag{1}$$

IF represents the increase ($IF > 1$) or decrease ($IF < 1$) in wind loads on the principal building due to interference. An *IF* of 1 suggests no effect due to interference as in an isolated building condition. The detailed experimental results have been analyzed and simplified to yield simple Interference Influence Grids, generalized guidelines and regression equations.

3.1. Mean loads

The mean loads are reduced due to the effects of interference that translates to a beneficial *shielding* when two buildings are arranged in tandem. Shielding is a special case of interference in which wind loads on a building are actually reduced due to obstruction of wind flow by an upstream building. This shielding manifests itself in a significant reduction in mean along-wind force (drag) on the principal building placed in tandem, behind the upstream building, especially for a 0° wind direction normal to the building face.

Fig. 4 shows *IF* (see Eq. (1)) contours for mean drag coefficient ($\overline{C}_d$) on the principal building due to an identical adjacent building at various locations around it. The $\overline{C}_d$ for isolated building is 1.30 (Khanduri 1997). The extent of shielding is immediately apparent from the figure. The value of *IF* for the principal building when the interfering building is located at $Sx \approx 11b$ is 0.70 which indicates a 30% decrease in mean drag. This means that a downstream building experiences

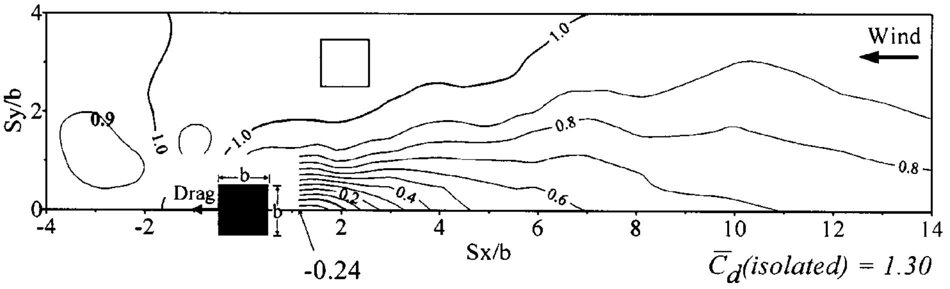

Fig. 4 Effect of interference on mean drag in terms of Interference Factors (*IF*)

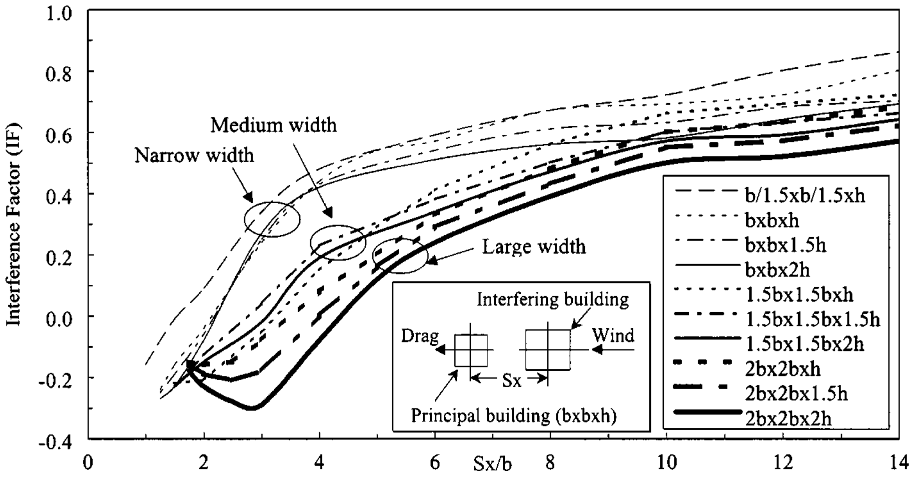

Fig. 5 Interference Factors for interfering buildings of various sizes

considerable shielding due to an upstream building located as far away as 11 times the building width or 220 m, in full scale, in this case. The shielding increases to 50% at $Sx \approx 5b$. At $Sx \approx 2b$, *IF* becomes zero suggesting an absence of drag force on the principal building or, in other words, a complete shielding of the principal building by the upstream building.

Fig. 5 shows the variation of *IF* with normalized along-wind spacing, Sx/b between two interfering buildings, for ten interfering building sizes. The mean loads are reduced ($IF < 1$) for all tandem arrangements. However, for close separation (less than $2b$, where b is the width of the principal building), the principal building may experience severe suction ($IF < -0.10$), i.e., a pull directed towards the interfering building. In case of close tandem locations, both buildings are completely submerged in the wake of the upstream building, the pressure on the windward face of the principal building is reduced drastically due to the almost complete shielding provided by the upstream building. The reduction is so high that the usual pressure on this face changes into suction on account of the high velocity eddies forming in between the small gap between the two buildings. Moreover, the two close-spaced buildings almost replicate a rectangular building with a larger along-wind length so that the velocity of the flow reduces considerably on reaching the leeward end of the principal building, reducing the suction on its leeward face and hence the principal building experiences a reduction in overall drag. The shielding effect of the interfering building is felt from as far as 12 times the building width, reducing the mean drag on the principal building by 30%. Shielding is more sensitive to upstream building width than to its height. This is evident, for instance, from the curve representing *IF* for an interfering building size of $2b \times 2b \times h$ (where h is the height of the principal building) which lies below the $b \times b \times 2h$ curve, indicating a lower *IF* or drag (higher shielding) for the building with larger width. Moreover, curves with similar interfering building cross-sections show similar trends. These curves broadly fall into three distinct interfering building categories, viz. narrow, medium and large buildings.

The shielding effects data generated through wind tunnel experiments and shown in Fig. 5 is modeled empirically taking into consideration the building geometry and building spacing. Shielding effects are modeled for a 0° incident wind angle since it gives the absolute maximum shielding for buildings in tandem. Interference Factors (*IF*) for various interfering building geometries are taken from Fig. 5. A normalized separation variable, s, combining and relating Sx and the building geometries is defined as,

$$s = \frac{Sx}{b}\left[\frac{b_r^2 + h_r^2}{b_r h_r}\right] \tag{2}$$

where $b_r = b_i / b$ and $h_r = h_i / h$; Sx = centre-to-centre spacing between the principal and interfering building, b and b_i, h and h_i are the widths and heights of the principal and interfering buildings, respectively. The above equations result from the evaluation of several different criteria for normalization, and provide a good correlation between IF and s. Thus, three appropriately normalized data sets, representing in general buildings of narrow, medium and large cross-sections, for IF versus s are prepared for modeling. Employing least squares optimization, the following three equations representing the shielding effects of the upstream building on a downstream building are obtained. The goodness of fit is evaluated by computing the mean squared error (*MSE*) over the entire data range, a low value signifying a better overall fit.

(a) Interfering building of *narrow width* ($b_i = b$; $h \leq h_i \leq 2h$) :

$$IF = 0.7 - 1.6e^{-0.18s} \quad \text{(MSE = 0.0045)} \tag{3}$$

(b) Interfering building of *medium width* ($b_i = 1.5b$; $h \leq h_i \leq 2h$) :

$$IF = 1.9e^{-0.01s} - 2.0e^{-0.07s} - 0.5 \quad \text{(MSE = 0.0023)} \tag{4}$$

(c) Interfering building of *large width* ($b_i = 2.0b$; $h \leq h_i \leq 2h$) :

$$IF = 1.9e^{-0.01s} - 2.0e^{-0.06s} - 0.5 \quad \text{(MSE = 0.0045)} \tag{5}$$

The above equations can be used to obtain a good estimate of the shielding effects of upstream buildings of sizes up to twice that of the principal building. More details of the modeling process can be found in Khanduri *et al.* (1998a). The experimental data along with fitted curves and some literature results is shown in Fig. 6. It can be seen that the actual and modeled results match reasonably well.

3.2. Fluctuating loads

The fluctuating or dynamic loads are expressed in terms of the standard deviation of fluctuating drag in the along-wind direction and fluctuating lift in the across-wind direction. Results show that while the effect of interference on mean loads is generally beneficial (shielding), it is exactly the reverse in case of fluctuating loads, which generally increase due to interference. The fluctuations in drag are almost entirely due to the action of the incident turbulence of the longitudinal component of the wind velocity. However, the unsteady lift results from the alternate vortex shedding from the two sides of the building, which may cause the building to vibrate laterally. Interference due to an adjacent building causes significant changes in the incident turbulence as well as the vortex shedding and, therefore, alters the fluctuating forces on a building. Fig. 7, based on the results of wind tunnel experiments, shows IF contours for fluctuating drag coefficient for the principal building due to an adjacent building at various locations around it.

The increase in fluctuating drag is immediately apparent. In Fig. 7(a) the largest IF of 1.6 is obtained upstream at $Sx = 3b$ and $Sy = 0.75b$, which indicates an increase of 60% over the isolated

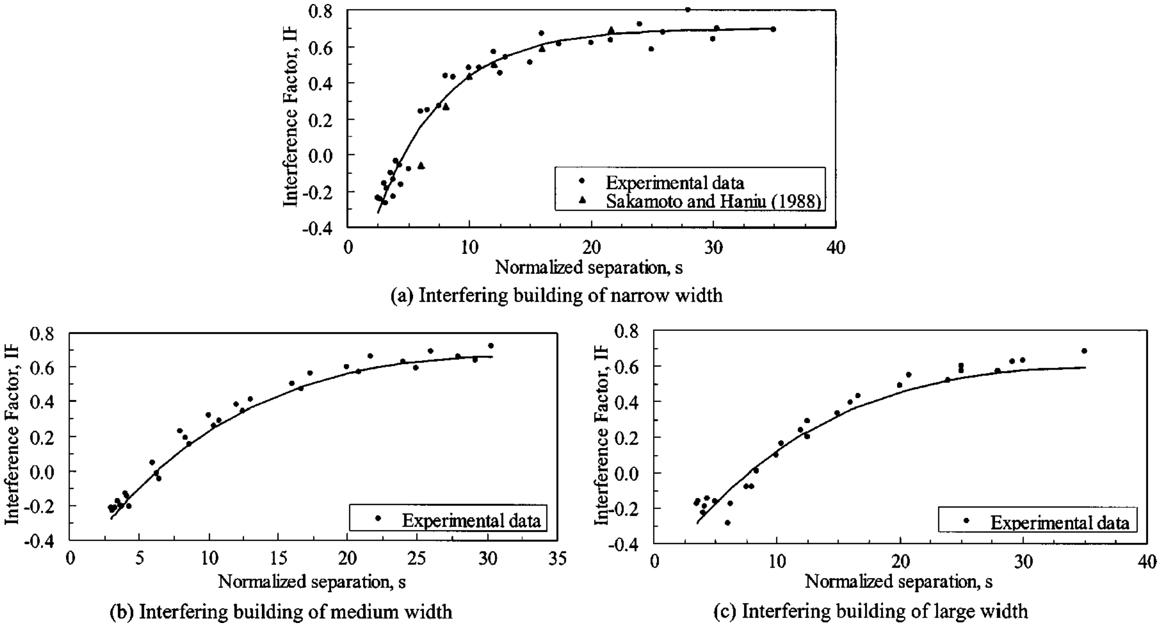

Fig. 6 Empirical curves for prediction of Shielding Factors

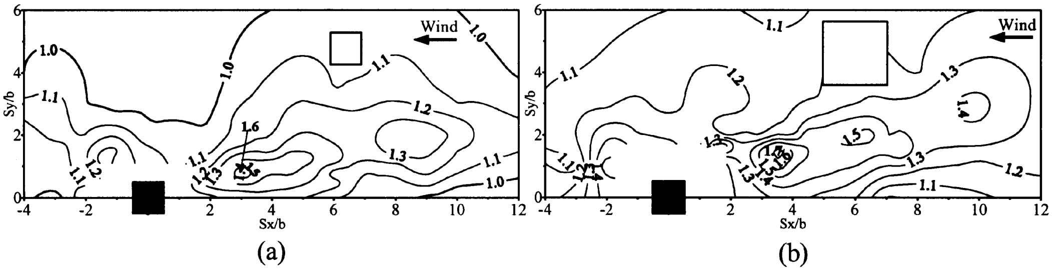

Fig. 7 Interference Factor (*IF*) contours for fluctuating drag (a) Principal and Interfering buildings of similar size (b) Interfering building double the size of principal building

building fluctuating drag coefficient of 0.25 (Khanduri 1997). As shown in Fig. 7(b), the fluctuating drag increases with the size of the interfering building. An increase in fluctuating drag of 70% is obtained when a building double the width of the downstream building, is located at $Sx = 3.5b$ and $Sy = 1.5b$. The results for fluctuating lift are shown in Fig. 8. Saunders and Melbourne (1979) have reported similar increases, in along-wind and across-wind dynamic moments of a square shaped building, due to interference from buildings of various sizes.

Fig. 9 shows the effect of angle of attack of wind on mean drag coefficient. It is noteworthy that the ridge of the contours in each case is oriented in the direction of the incident wind and the contours exhibit a great degree of symmetry about this ridge. When the interfering building is positioned along this ridge, the downstream building lies within the wake of the upstream building and is thus subjected to high shielding.

Fig. 10 shows the effect of upstream exposure on mean drag ($\overline{C}_d$) Interference Factors (*IF*). The values of $\overline{C}_d$ for isolated buildings are 1.30, 1.15 and 1.02 for open, suburban and urban exposure,

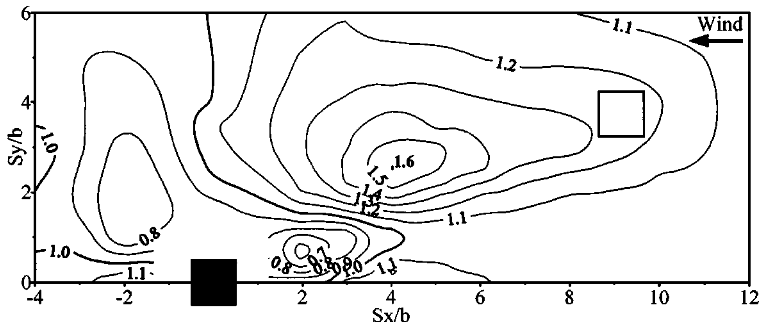

Fig. 8 Interference Factor contours for fluctuating lift

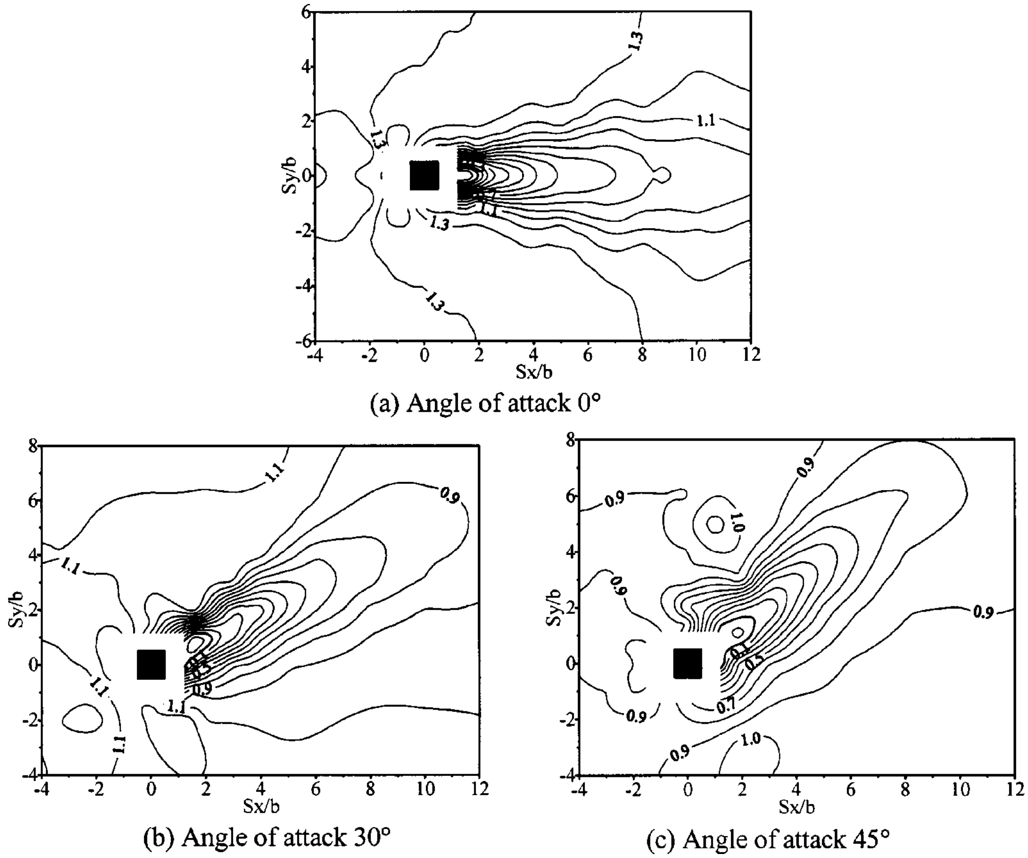

Fig. 9 Effect of angle of attack of wind on mean drag coefficient

respectively (Khanduri 1997). The open exposure shows the most severe interference effects, especially with regards to shielding. For example, when a building is placed in front of the principal building at a centre-to-centre distance of 10(b) upstream, $\overline{C}_d$ on the principal building is reduced by 28% ($IF = 0.72$), 22% ($IF = 0.78$) and 12% ($IF = 0.88$) for open, suburban and urban exposure, respectively. Fig. 10(c) shows that *IF* remains near 1.0 over a large region, indicating the minimal effect of the interfering building on $\overline{C}_d$ of the principal building for an urban exposure. The properties

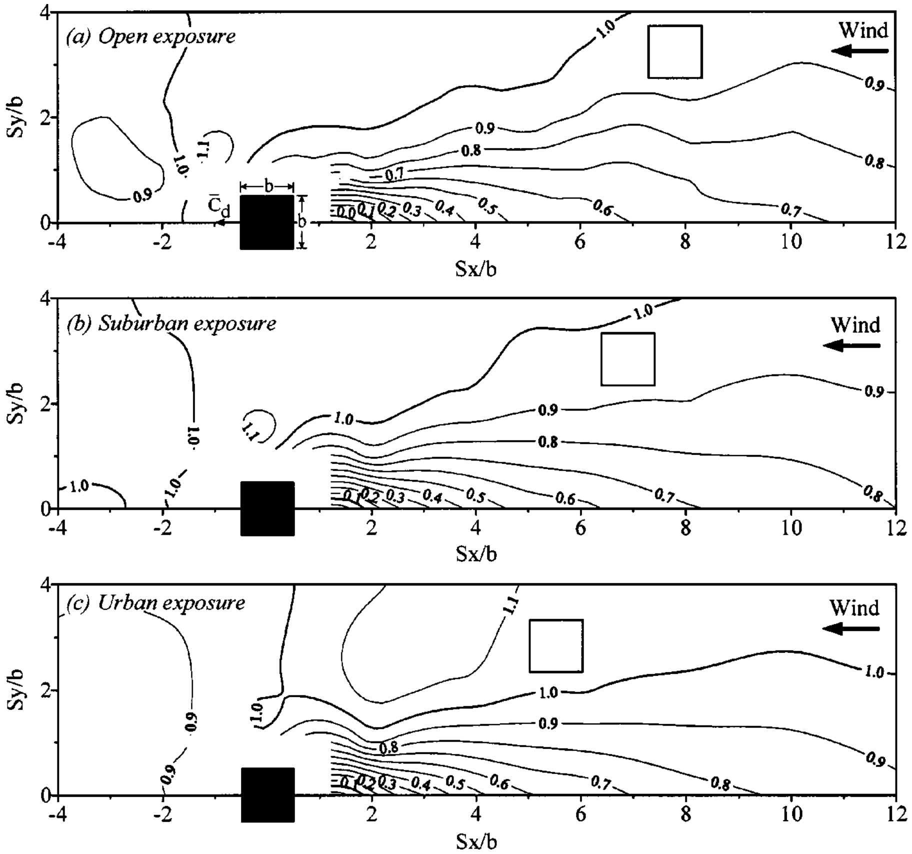

Fig. 10 Effect of upstream exposure on mean drag IF

Table 1 Properties of the three upstream exposures

Exposure	Power law exponent, α	Turbulence intensity, I_v^* (%)
Open	0.15	7
Suburban	0.25	13
Urban	0.36	25

*At building height

of the three upstream exposures are summarized in Table 1.

4. Towards design: simplification and generalization

A detailed experimental program, while tackling complex issues, also generates large amounts of data, which sometimes can be difficult to interpret and can also be cumbersome to put into practical use. The building designer needs, primarily, a quick idea of the extent and the severity of the problem at hand. In the case of wind design, a preliminary, simplified "tour" of the interference effects problem can help the designer differentiate between critical and unimportant cases. It may also help one judge, to a good degree of approximation, the severity of interference effects. Based

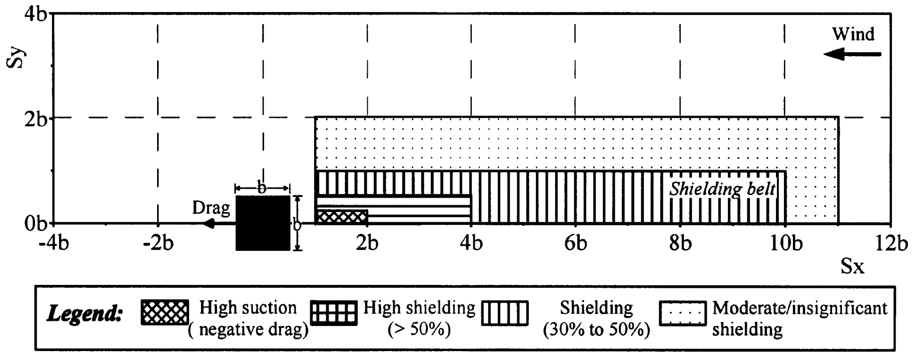

Fig. 11 Interference Influence Grids for mean loads

on the prevalent conditions, the designer can then exercise judgement whether to ignore the case, go for a thorough analysis or carry out detailed wind tunnel experiments. The need, therefore, is to simplify the problem, while retaining its basic intrinsic nature.

The experimental results have been simplified and presented from the point-of-view of design and codification. Some approximations have been made to render results viable for practical use. For instance, the areas of significant interference effects have been approximated by rectangles rather than curves. However, care has been exercised to ensure that these approximations retain the essential characteristics of actual cases. The entire experimental data is simplified by highlighting the most important aspects and neglecting others that appear less critical. The resulting Interference Influence Grids (IIGs) present an overall simplified, yet comprehensive view of wind-induced interference effects.

Fig. 11 presents IIGs for mean loads. The figure shows locations around the principal building where an identical interfering building would cause significant shielding on the principal building. The *shielding belt* shows reductions in mean drag. Locating the interfering building within this belt produces beneficial shielding on the principal building. For example, in Fig. 11 a shielding of 30% implies an IF of 0.70 or a 30% reduction in drag force on the principal building. As the spacing between the two buildings is decreased, shielding increases. For very close spacings ($Sx < 2b$) suction on the windward face of the principal building becomes larger than on the leeward face, thus generating a net negative drag on the principal building.

Fig. 12 presents IIGs for fluctuating loads. It shows locations around the principal building where an identical interfering building would create significant interference effects in terms of fluctuating drag and lift forces on the principal building. The shaded regions represent, in general, increases in fluctuating loads due to interference. The unshaded areas are the locations of insignificant interference effects. The bi-directional arrows show the direction of the force, horizontal for fluctuating drag and vertical for fluctuating lift.

Fig. 13 shows Interference Influence Grids for buildings of different size. Note that the interfering building is up to twice the width and the height of the principal building and the effective areas represent envelopes of the measured data for different configurations. Fig. 13(a) shows the influence on mean and fluctuating drag force whereas Fig. 13(b) refers to mean lift coefficient. Percentages represent changes in loads with respect to the reference cases of Figs. 11 and 12. For isolated buildings, mean drag and mean lift coefficients are 1.3 and 0.0, respectively and fluctuating drag and fluctuating lift coefficients are 0.25 and 0.35, respectively (Khanduri 1997). The high increases

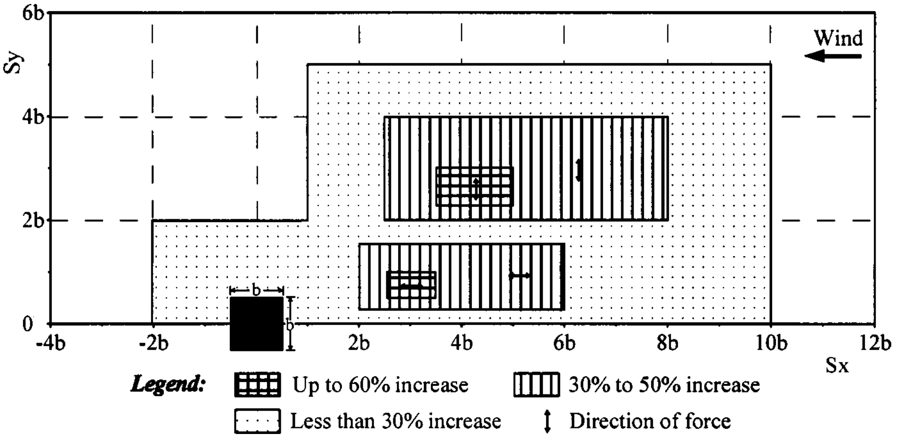

Fig. 12 Interference Influence Grids for fluctuating loads

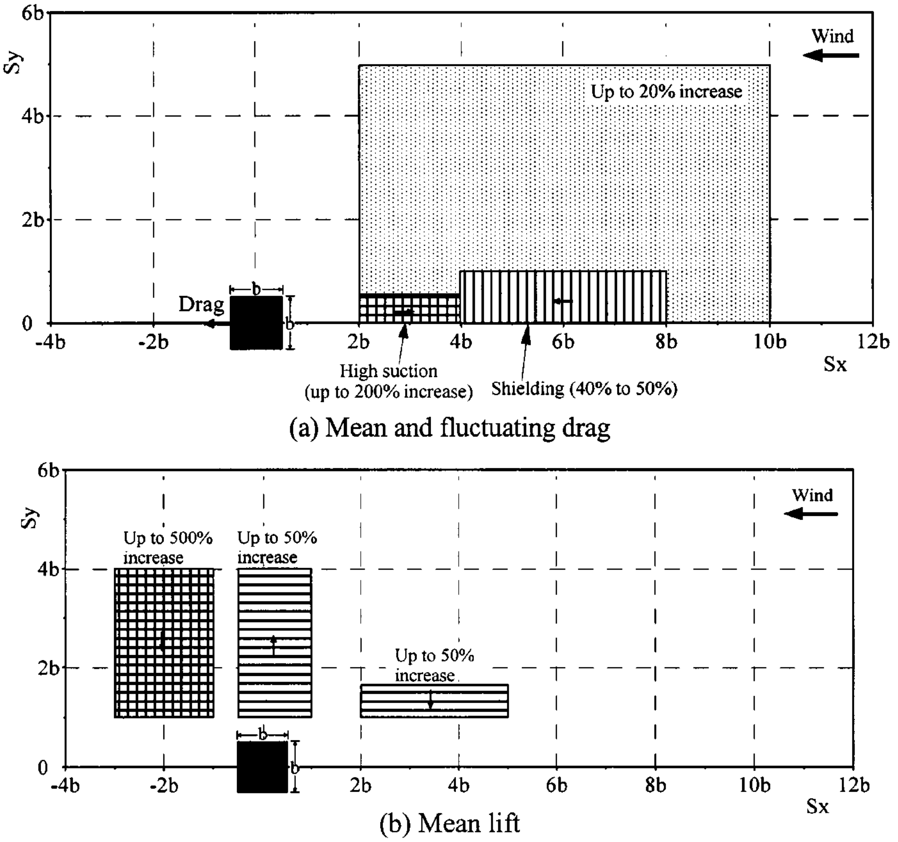

Fig. 13 Size Influence Grids - Effect of interfering building size on mean and fluctuating loads

of Fig. 13(b) correspond to the taller interfering building when found in the shown locations.

Simplified diagrams like those of Figs. 11, 12 and 13 can guide the designer as to the likely influences of interfering buildings. However, detailed quantification of the interference effect for a specific case of interest would still require physical simulation in the boundary layer wind tunnel.

5. Conclusions

Detailed experimental results on interference effects for two buildings have been presented by way of interference effect contours. From a practical, design standpoint, the entire bulk of data has been synthesized in the form of simple, easy-to-understand Interference Influence Grids (IIG). Such simple templates can be used for a quick, preliminary analysis and estimation of wind-induced interference effects; they may also form the basis of some form of codification.

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