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CHARACTERISTICS OF AERODYNAMIC RESPONSE OF HIGH-RISE BUILDINGS WITH OPEN PASSAGE

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Abstract

This paper describes the effectiveness of introducing aerodynamic response control method for mitigating the response and the experimental results of across-wind aerodynamic responses by using several dynamic models with open passage configurations. On the whole, air flow going through open passages can work in effective way to reduce aerodynamic responses. In this study, the dependence of the aerodynamic responses on the sectional configuration or vertical position of open passage is discussed. From a point of the damping coefficient, sections with along-wind open passages tend to obtain relatively more aerodynamic effect, while across-wind open passages have an adverse influence on the separated shear layer. As for the vertical height of open passages, aerodynamic responses are the most reduced in the case of open passages introduced on 0.8 to 0.9 of reference height.

Keywords: Across-wind aerodynamic response, Open Passage, High-rise Building

1. Introduction

As for the across-wind aerodynamic response of high-rise buildings, several ways for mitigation of the response have been attempted based on the aerodynamic modification of the sectional configuration, for example, which are shapes with chamfered, slotted corners or fins in passive way (e.g., Kawai,H et al. 1994; Miyagi,T et al. 1998; Suda,K et al. 1996; Shiraishi et al. 1986; K.C.S.Kwok et al. 1981; and others) and shapes with rotors or jets in active way (e.g., Okanan,H et al. 1990; Yoshida,A et al. 1996; and others). These methods are attempted in the point of controlling air flow inside region of separated shear layer or periodic generation of vortex inside negative pressure region, which leads to improving aerodynamic properties to suppress wind force coefficients. Therefore, these methods can be called as "aerodynamic response control method" as compared with "structural response control method" such as using active mass damper.

Based on the aerodynamic response control method, authors evaluated possibilities for mitigation of across-wind response by carrying out dynamic experiments on the high-rise building model with open passages (e.g., Okana,H et al. 1997; Kikitsu,H et al. 2000). Aerodynamic modification of the section with open passages has an aim to affect separated flow near side wall or dead region near leeward wall by introducing upwind positive air flow to these regions. Other studies by Dutton,R et al.(1990), Katagiri,J et al.(1992) and Noda,H et al.(1994) on the aerodynamic modification with open passages carried out force balance experiments and presented meaningful results that the introduction of open passages leads to reduction of across-wind RMS force coefficients and also shifts the spectral peak to a somewhat higher reduced velocity conservatively.

Based on results of dynamic experiments, this paper discusses and describes the influence of the open passage on the characteristics of across-wind aerodynamic responses and their generating mechanism by setting the side ratio of the model, sectional configuration and introducing height of the open passage as experimental factors to be considered.
2. Outline of Wind Tunnel Experiment

2.1 Experimental wind

Dynamic experiments were carried out at the boundary layer wind tunnel facility in Building Research Institute. The wind tunnel is 25m long, 3m wide and 2.5m high. Fig.1 shows wind profile used in this experiment. This wind profile has a power law index of approximately 0.25 which corresponds to the roughness terrain category III regulated in AI(1993). The intensity of the turbulence is 10% at reference height of the model and the depth of the boundary layer is approximately 1,000mm.

2.2 Experimental model

The scale to be considered in these experiments is 1/4 for wind velocity, 1/500 for length and 1/125 for time respectively and the model can be corresponding to high-rise building with reference height of approximately 300m in full scale. Fig.2 shows three types of the experimental models. The patterns of the side ratio are D/B = 1/2, 2/3, 1.0, 3/2, 2.0 (D: depth, B: width) and all of them have aspect ratio of 8.0. The introducing heights of open passage are 0.6H, 0.7H, 0.8H and 0.9H (H: reference height) and the height of each one is 20mm. Four open passages are introduced on every wall and they are connected one another in the same height. These models have stiffness coefficients of 19,600 × 2N/m for across-wind direction and 68,600 × 2N/m, natural frequency of 14.7Hz and structural damping coefficient of 0.67%, respectively. Dynamic deflection in across-wind direction is measured by razor measurement device with sampling frequency of 500Hz and sampling number of 2048.

![Fig.1 Experimental Wind Profile](image1)

![Fig.2 Configuration of Experimental Models](image2)

3. Results of Wind Tunnel Experiment

In the following, results of wind tunnel experiments are presented. They are discussed based on several experimental factors such as side ratio of the model, sectional configuration and height of the open passages.

3.1 Influence of configuration of open passage on characteristics of across-wind aerodynamic response

In this section, based on the configuration of the introduced open passages, the results of across-wind aerodynamic response under strong wind with return period of approximately 100 years are discussed. As shown in Fig.3, four patterns of section configuration including basic section are considered and all of the open passages are introduced at height of 0.9H. In the following, the four patterns are designated N (basic section), A (section with along-wind open passage), B (section with across-wind open passage) and C(section with along and across-wind open passage).
Fig. 4 shows the results of the measured across-wind aerodynamic responses of each pattern of side ratio. Vertical axis indicates normalized rms deflection corresponding to the standard deviation of the tip deflection divided by width B and horizontal axis indicates reduced wind velocity $U^*$ corresponding to the wind velocity divided by both of across-wind natural frequency and width B. As for the result of side ratio of 1.0, there is a difference of response from $U^* = 10.0$ approximately, depending whether there are open passages or not. The response in pattern A is greatly reduced by half of that in pattern N. As for the results of side ratio of 0.67 and 0.5, the responses in patterns with open passages also decrease compared with that in pattern N from $U^* = 7.0$ approximately. According to the above results, it appears that the introduction of open passage is effective for mitigation of across-wind aerodynamic response and that patterns A and C with along-wind open passages have relatively more effective than pattern B only with across-wind open passages.

Fig. 5 indicates measured power spectra of across-wind tip deflection in order to evaluate the influence of air flow through open passages in the vortex region. In this case, the building model of side ratio of 0.67 with all stories’ passages open is used to highlight the effect of introducing open passages. At low wind speed as shown in Fig. 5 (a), patterns N, B and C have distinct spectral peak in Strouhal frequency, while pattern A only with along-wind open passages do not have such peak. This result can regarded as almost the same phenomenon as the effect of a jet supply (Okanan,H et al. 1990) to a dead region in that air flow to the dead region directly controls the periodic generation of vortex. As shown in Fig. 5 (b) at resonance wind speed patterns N and B have almost the same spectral peak in natural frequency, while patterns A and C with along-wind open passage display much lesser value.
From the results as shown in Fig.4 and 5, it is concluded that along-wind open passages are more advantageous in mitigating across-wind aerodynamic response than across-wind open passages.

Fig. 5 Measured Power Spectra of Across-wind Tip Deflection

Fig.6 indicates aerodynamic damping coefficients extracted by auto-correlation method in order to evaluate aerodynamic damping effects. On the whole, the tendencies of the effects in each side ratio of 1.0 are as follows: (i) coefficients in side ratio of 1.0 have maximum value in $U^* = 10.0$ approximately and then decrease with reduced velocity increasing, (ii) coefficients in side ratio of less 1.0 decrease with reduced velocity increasing and (iii) coefficients in side ratio of more 1.0 increase with reduced velocity increasing. And it can be seen that pattern A only with along-wind open passage have relatively more aerodynamic damping effect and that pattern B only with across-wind open passage have relatively less effect than pattern N. If this result is considered to be the same phenomenon as the configuration with chamfered section aerodynamically, it can be a regarded that pattern B weakens the aerodynamic damping effect since air flow through side wall prevents separated flow from reattaching and widens the width of the wake. These were also discussed previously by Shiraishi, N et al.(1986) thus verifying the experimental results of the relationship between the chamfered size and the degree of the separated flow’s reattachment.

3.2 Influence of height of open passage on characteristics of across-wind aerodynamic response

Generally, it is considered that characteristics of across-wind aerodynamic response based on the aerodynamic response control method depend on the difference of upwind angle and height of aerodynamic treatment. Accordingly in this section, results of across-wind aerodynamic response are discussed taking notice of height of open passage. Fig.7 shows normalized rms values of across-wind tip deflection of pattern A which is evaluated to result in obtaining the most aerodynamic damping effect. As for the side ratio of 1.0, the difference of the response from $U^* = 8.0$ depends on whether there is open passage, but not against height differences. As for side ratio of less 1.0, it is evident that there is a marked contrast between the introduced height of 0.6H or 0.7H and that of 0.8H or 0.9H and that the latter is more effective for mitigating the response. In particular, it is noted that the response of side ratio of 0.5 with open passage’s height of 0.6H or 0.7H increases more than that of pattern A, which results in adverse effect. Kareem, A et al.(1999) also point out this aerodynamic tendency. There
is no significant difference between the results for the case of the side ratio of greater than 1.0, compared with other cases of side ratio.

In the case of the across-wind aerodynamic response of vibration system with very low damping coefficient, the peak values of the random process can be fitted by Rayleigh distribution and, on the other hand, its behavior approximates to the cumulative distribution function of peak values of sine curve process when the interaction between the response and added aerodynamic force is pronounced (K.C.S.Kwok et al. 1981; W.H.Melbourne et al. 1975). Based on this information, the influence of height of open passage on the mechanism of generating across-wind aerodynamic response is further discussed by the characteristics of cumulative distribution function of measured value. Fig.8 shows the cumulative distribution function $F_x$ of measured peak values for side ratio of 1.0, 0.67, 0.5 and 1.5. These values were measured under normalized wind velocity with return period of 100 years in full scale. Horizontal axis indicates reduced amplification divided by standard deviation and vertical axis indicates reduced variable of cumulative distribution function based on the Hazen plot method as follows:

$$F_x(x_i) = 1 - \frac{2^{2i-1}}{2N} \left( x_i \geq x_j \geq \Phi \geq x_i \geq \Phi \geq x_N \right)$$  \hspace{1cm} \text{Eq.1}$$

The cumulative distribution function of peak values in narrow-band random process can be expressed as follows:

$$F_x(x) = 1 - \exp \left[ -\left( \frac{x}{\sqrt{2}} \right)^2 \right]$$  \hspace{1cm} \text{Eq.2}$$

The values $k$ and $c$ of Weibull distribution as shown in Eq.3 are $k = 2$ and $c = \sqrt{2}$ for the above narrow-band random process and $k = \infty$ and $c = \sqrt{2}$ for the sine curve process, respectively.

$$F_x(x) = 1 - \exp \left[ -\left( \frac{x}{c} \right)^k \right]$$  \hspace{1cm} \text{Eq.3}$$

Fig.9 shows the values $k$ and $c$ for the cumulative distribution function of measured peak values shown in Fig.8. In this calculation, upper 5 or 10% peak values of all are used for fitting. It can be said that peak values in every case fit moderately with Weibull distribution and that the characteristics of the distributions depend on side ratio and height of open passage. As for the side ratio of 1.0 or less, with the height of open passage getting lower, the value of $k$ increases and the distribution approaches that of sine curve, which indicates that the influence of interaction between the across-wind aerodynamic response and the added aerodynamic force is negligible. In particular, as for side ratio of 0.5, the value of $k$ for heights of 0.6H and 0.7H are considerably greater than that for pattern N and the result agrees with the adverse effect as shown in Fig.7. As for side ratio of more than 1.0, the characteristics of distributions do not depend on the height of open passage and almost the same as that of narrow-band distribution function with $k = 2$. The values $c$ in every case are approximately $\sqrt{2}$. 

519
Fig. 7  Normalized rms Values of Across-wind Tip Deflection (focused on the vertical height of open passage)

According to the above results, it can be concluded that the heights of open passage of 0.8H and 0.9H are effective in mitigating the influence of added aerodynamic force and that the height of 0.6H has a possibility to cause the adverse influence, particularly for side ratio of less than 1.0.

Fig. 8  Provability Distributions of Across-wind Peak Deflection
Conclusions

In this study, the dynamic experiments of high-rise building models with open passages were carried out and the effects of mitigating across-wind aerodynamic response were discussed considering side ratio of the model, sectional configuration and height of the open passage. In general, the sectional configuration together with open passage as the passive aerodynamic response control method can be regarded as effective in mitigating across-wind aerodynamic response.

In the following, the results on the characteristics of across-wind aerodynamic response and its generating mechanism are summarized.

(i) As for sectional configurations with along-wind open passage, aerodynamically stable effect is obtained with the across-wind response suppressed, since upcoming air flow through open passage controls negative pressure region near the leeward wall.

(ii) As for sectional configurations with across-wind open passage, although the across-wind aerodynamic response itself is less than that of sectional configuration without open passage, the aerodynamic damping effect tends to be weakened, since air flow from side wall prevents separated flow from reattaching and the width of the wake is widened.

(iii) In the case of the along-wind open passage, the height of 0.8 to 0.9H is considered to achieve the most agreeable effect for mitigating across-wind response. On the other hand, sections with open passage of height of 0.6H revealed adverse effects which is believed to be due. The influence of the interaction between across-wind aerodynamic response and added aerodynamic force as evaluated by the characteristics of cumulative distribution function of peak values.
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