

Internal stresses in cladding support members of long-span arched roof under wind load

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ABSTRACT: This paper discusses the largest wind load effects on roof cladding support members of a large-span arched roof. The contributions to member stresses due to overall wind effects and local wind effects were investigated using finite element model (FEM) analysis. Wind-induced pressures including mean and fluctuating components were measured on the roof of a 1:400 scale model under a suburban boundary layer wind flow. Measured wind pressures from limited measurement points were expanded to all the structural nodes using the orthonormal coordinate system obtained from the Proper Orthogonal Decomposition (POD) method. The largest load effects (focusing on member stresses) due to overall wind effects were estimated based on the quasi-static method and compared with those estimated by the time-domain analysis of the complete finite element model directly applying the expanded wind load. The contributions due to overall wind effects and local wind effects were compared.

KEYWORDS: Roof cladding-support members; Large-span arched roof; Overall wind effects; Local wind effects; Largest wind load effects; Contributions to largest load effects.

1 INTRODUCTION

Large-span roof structures usually have the characteristics of light mass, high flexibility, slight damping and low natural frequencies. Consequently, their structural systems are more wind sensitive than conventional roofs, and wind load is very important in structural design. Extensive investigations on the characteristics of wind loads and wind-induced responses of conventional roof structures have been conducted in the past ^[1-4]. Recently, equivalent static wind load methods based on the quasi-steady assumption have been widely used to reproduce largest load effects for structural members ^[5-7] and adopted in the building codes and laws of many countries, e.g. AIJ-RLB (2004) ^[8], ASCE/SEI 7-10 (2010) ^[9], and AS/NZS 1170.2 (2002) ^[10]. The researches mentioned above focused mostly on estimation of overall wind effects on main structural frames of conventional roof structures.

Large-span roof structures generally consist of main structural frames, roof cladding support members and roofing members. Obviously, stresses in roof cladding support members are affected by local wind pressures and tributary areas. They may also be affected by deformations of main structural frames due to overall wind effects. However, in current wind load codes, both roof cladding support members and roofing members are usually classified as components and cladding, and the wind load effects on such members are determined by local wind pressures and tributary areas only. By ignoring the influence of wind-induced responses of main structural frames, stresses in roof cladding support members are underestimated by current wind load codes.

Arched roofs are widely used for large-span structures such as entertainment or exhibition centers, closed sport buildings, aircraft hangars, etc. The largest wind load effects on roof cladding support members on these roofs are investigated in this paper, focusing on the contributions to member stresses due to overall wind effects and local wind effects. Mean and fluctuating wind pressures were measured simultaneously from the roof of a 1:400 scale model under suburban

boundary layer wind flow. Measured wind pressures were expanded from limited measurement points to all the structural nodes using the orthonormal coordinate system obtained from the Proper Orthogonal Decomposition (POD) method. The largest member stresses due to overall wind effects were estimated based on the quasi-static method. By extracting member stresses due to overall wind effects from those estimated by time-domain analysis of the complete finite element model applying the expanded wind load directly, member stresses due to local wind effects can be obtained. This paper compares the contributions to the largest load effects (maximum and minimum member stresses) due to overall wind effects and local wind effects.

2 MEMBER STRESSES DUE TO OVERALL WIND EFFECTS OR LOCAL WIND EFFECTS

Since the roof cladding support members of large-span roofs support the roofing members, the local wind pressures acting on the tributary areas can cause member stresses, called stresses due to local wind effects. However, roof cladding support members are themselves supported by the main structural frame. The wind-induced responses of the structural frame can also influence roof cladding support member stresses, called stresses due to overall wind effects. The extent of this influence depends on the characteristics of the connections between the roof cladding support members and the main structural frame (e.g., stiffness). The actual member stresses in these members under wind load are the combined stresses due to overall wind effects and local wind effects.

The actual member stresses were calculated by time-history analyses using the Newmark- β method with a completed FE model including a main structural frame and roof cladding support members. The deformations of the main structural frame were also analyzed. Generally, roof cladding support members are much smaller than main structural frame members. The additional stiffness to the main frame due to the roof cladding support members can be neglected, so the deformation of the main structural frame can be assumed to represent the overall wind effect on the entire structure. Since the roof cladding support members were supported by the main frame, the displacements of the supporting points will cause internal stresses in the cladding support members, which were assumed as the stresses due to overall wind effects. Compared with the main structural frame, the natural frequencies and damping of such members were relatively high, and member stresses can be obtained by the quasi-static method. For a static displacement d_i occurring at a support point i , a specific load effect r (e.g. member stress) can be derived as:

$$r = R_i d_i . \quad (1)$$

Here, R_i is the value of the load effect r caused by unit displacement at a support point i . For displacements occurring at all support points i , the load effect r can be indicated as a superposition of Eq. (1). Following the quasi-static assumption, the load effect $r(t)$ can be expressed by:

$$r(t) = \sum_{i=1}^N R_i d_i(t) = \{R\}^T \{D(t)\} . \quad (2)$$

The largest load effect $\hat{r}$ can be indicated by:

$$\hat{r} = \{R\}^T \{\hat{D}\} . \quad (3)$$

As mentioned before, the actual member stresses in roof cladding support members under wind load are the combination of stresses due to overall wind effects and to local wind effects. Since the member stresses due to overall wind effects calculated based on the quasi-static method result from the actual member stresses, the components due to local wind effects can be extracted.

3 WIND TUNNEL EXPERIMENTS

3.1 Experimental arrangements

The wind tunnel experiment was carried out in a boundary layer wind tunnel at Tokyo Polytechnic University, Japan. The test section was 2.2 m wide and 1.8m high. Suburban terrain characteristics were simulated by spires and roughness elements with the power law exponent of mean wind speed $\alpha=0.16$. A velocity scale of 1/5 was adopted. The mean wind speed at reference height of the model (average height of the curved roof) was 8.5m/s and the corresponding turbulence intensity was approximately 14%, as shown in Fig. 1. The measured longitudinal spectrum of wind velocity at the reference height is shown in Fig. 2.

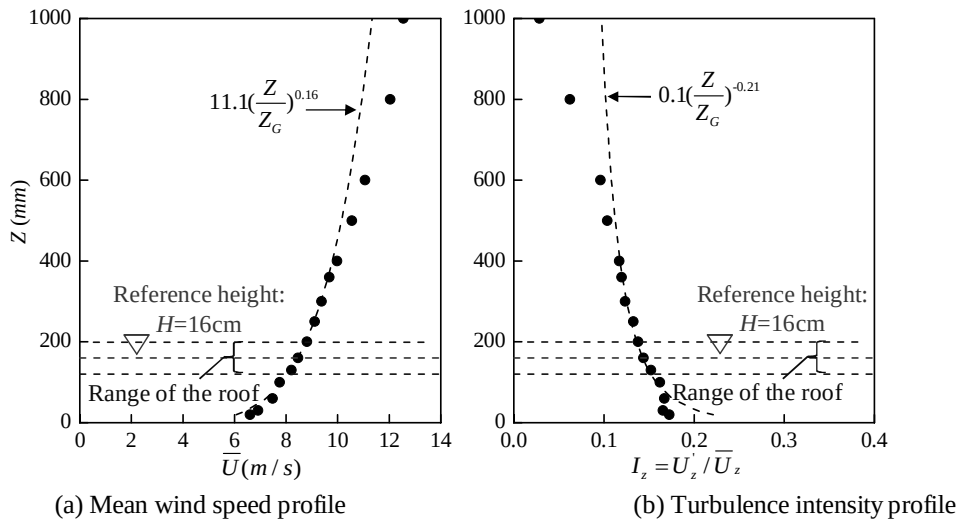


Figure 1. Measured longitudinal mean wind velocity and turbulence intensity profiles.

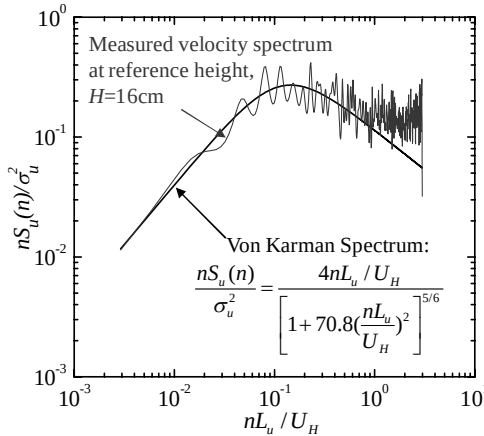


Figure 2. Measured longitudinal spectrums of wind velocity.

The geometric variables relevant to the wind loads on arched-roof buildings were: span, S ; length, L ; rise, h ; and height of walls to eaves level, H . The geometry of the 1:400 scale wind tunnel model is illustrated in Fig. 3(a) together with the coordinate system used in this study. The model has the span S equal to 40cm, corresponding to 160m in full scale. The rise/span ratio h/S was set to 0.2 while the length to span aspect ratio L/S was 1. The wall-height was 12cm. Fig.

3(b) shows a photo of the model mounted on a turning table in the wind tunnel. Pressure taps installed on the roof's upper surface are marked with • and numbers as shown in Fig. 4.

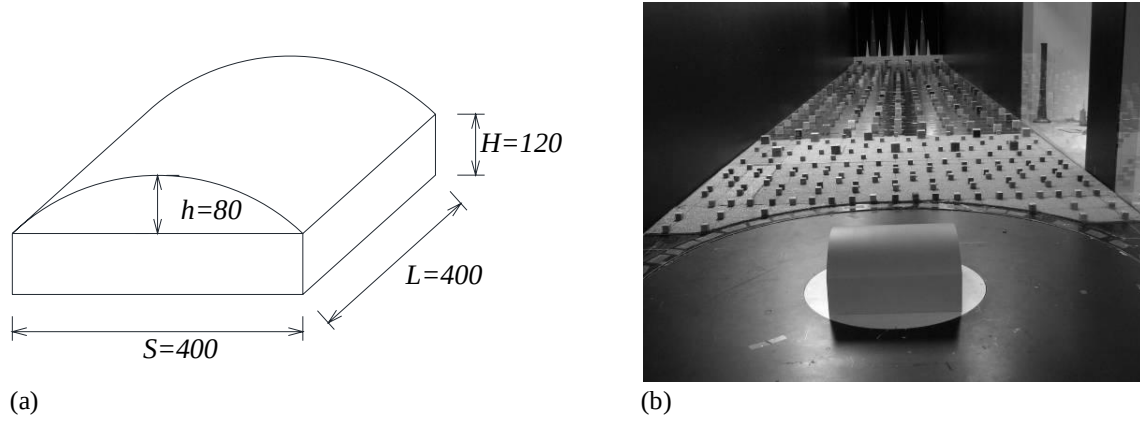


Figure 3. Experimental model (unit: mm). (a) Geometric variables of arched roof model, (b) photo of model in wind tunnel.

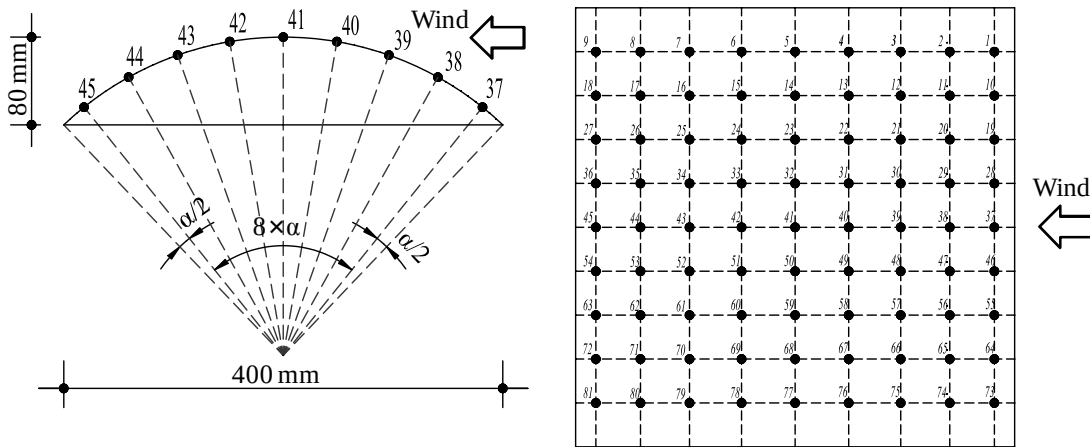


Figure 4. Distribution and numbering of measuring pressure taps for arched model.

Wind pressures were measured with a sampling frequency of 781 Hz using a multi-channel simultaneous fluctuating pressure measurement system. As the time scale of prototype vs. wind tunnel model was 1/80, the sampling frequency of the prototype was equivalent to 10 Hz. The tubing effects were numerically compensated by the gain and phase-shift characteristics of the pressure measuring system^[11].

3.2 Proper orthogonal decomposition

Since the effect of load distribution is important to the dynamic analysis of an arched roof^[12], it is necessary to expand the measured mean or fluctuating wind pressure data at limited measurement points to all the structural nodes on the surface of the roof by applying a proper orthogonal decomposition (POD) method. The eigenvalues λ_k and eigenmodes $\{\Phi\}_k$ were obtained by solving the following equation:

$$[R]\{\Phi\} = \lambda\{\Phi\} \quad (4)$$

where, $[R]$ represents the pressure space correlation matrix. The fluctuating wind pressure field $\{p\}$ can be expressed by:

$$\{p\} = \mathbf{\hat{a}}_k a_k(t) \{\Phi\}_k \quad (5)$$

where, $a_k(t)$ represents the k th orthonormal coordinate. The eigenvalue λ_k is the measure of the contribution of each eigenmode to the pressure mean squares, and is normalized as:

$$P_k = \frac{\lambda_k}{\mathbf{\hat{a}}_N \lambda_j} \quad (6)$$

The normalized eigenvalues P_k are plotted against the mode index k in Fig. 5 for wind directions $\theta = 0^\circ, 45^\circ$ and 90° . The accumulated values of P_k up to the 20th eigenmode were approximately 0.9 when the wind direction was 0° . In the following analysis, the wind pressures at the nodes were simulated by the first 20 eigenmodes. The values of $\{\Phi\}_k$ at the nodes of the structural model were interpolated or extrapolated from those at the tap locations given by the POD analysis.

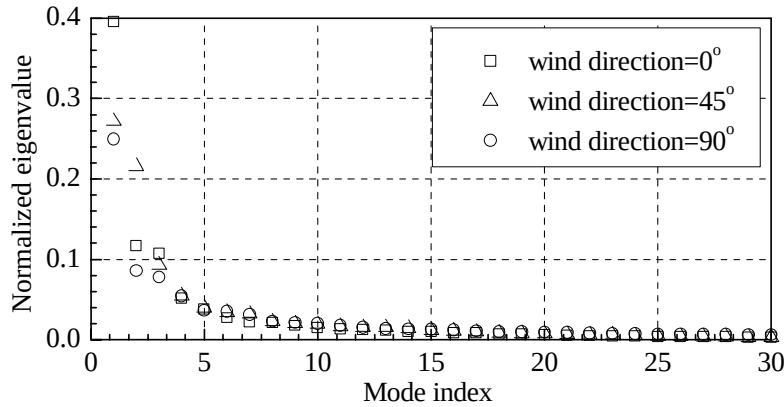


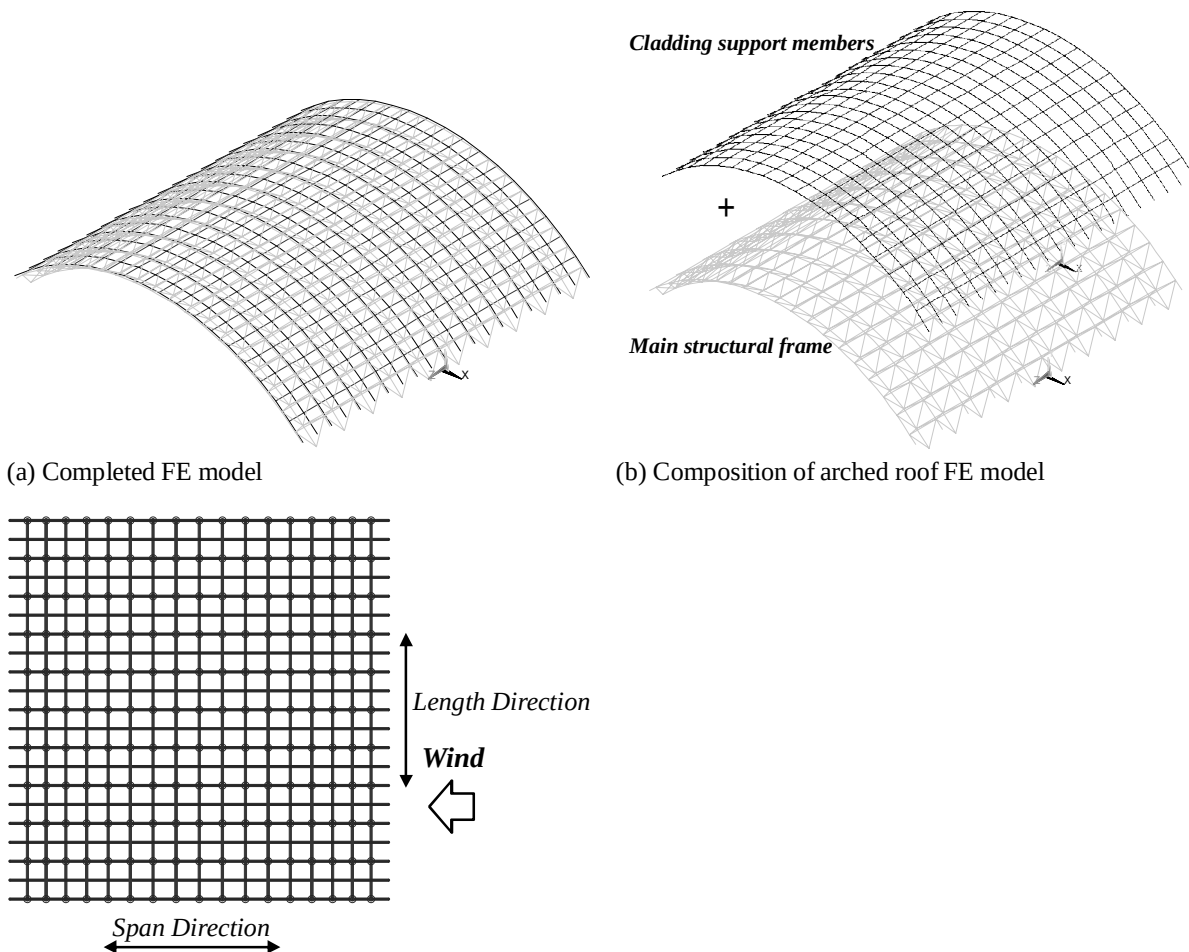
Figure 5. Normalized eigenvalues of fluctuating pressure.

4 ESTIMATION OF LARGEST STRESSES IN ROOF CLADDING SUPPORT MEMBERS

4.1 Structural model

As shown in Fig. 3, the wind tunnel test model was an arched roof model including walls, and pressure taps were installed only on the roof's upper surface. The prototype structure was assumed as a closed arched roof structure, in which the roof part was supported by walls or columns. Since the target in this study was the stresses in the roof cladding support members, only the roof structure was modeled by ANSYS software, following the length scale in the wind tunnel of 1:400. The finite element (FE) model of the roof structure was made up of a main structural frame and cladding support members, as shown in Fig. 6(a)-(b). All the joints on the bottom of the roof model were assumed fixed for all six degrees of freedom.

The cladding support members can also be classified as members along the length direction and members along the span direction. The members along the length direction were treated as continuous beams supported by the main structural frame. The support points are marked with $\circ$ in Fig. 6(c). Seventeen beams were arranged at equal intervals of arch length. On the other hand, members along the span direction were connected to adjacent beams and the connection conditions were assumed as rigid.



(c) Model of cladding support members

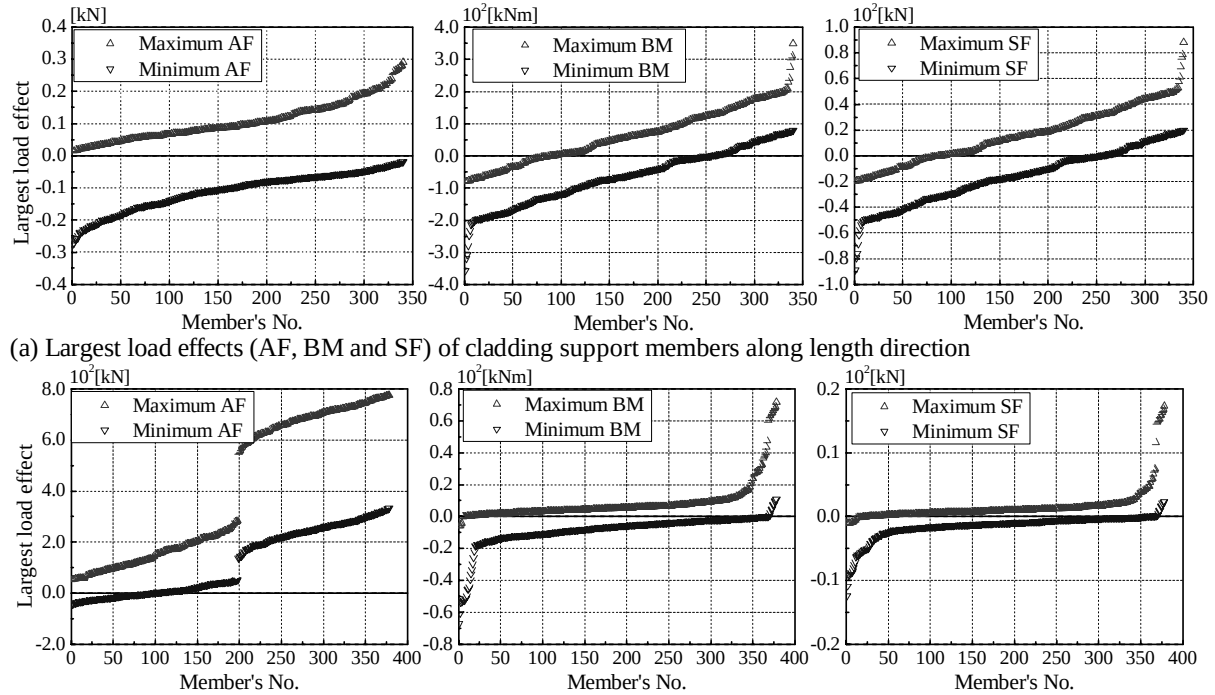
Figure 6. Structural model of arched roof structure: (a) completed FE model; (b) composition of arched roof FE model; (c) model of cladding support members.

4.2 Computation of largest load effect in time-history analyses

As mentioned in Sec. 2, the actual member stresses for cladding support members were computed in time-history analyses. The mean wind speed at the reference height ($H=64\text{m}$) was set at 42.5m/s . The critical damping ratios for the first and second modes were set to 1% to determine the two coefficients for the Raleigh damping equation. In the present study, the effects of aerodynamic damping and stiffness were not considered. Member stresses were analyzed for a duration of 11 min and the result for the first 1 min was not used for the statistical analysis because of the non-stationary state.

The loads on the arched roof were transmitted mainly by means of member axial force (hereafter referred to as AF), bending moment (hereafter referred to as BM) and shear force (hereafter referred to as SF). Torsional moment was neglected. Axial stresses in members were evaluated based on the combination of AFs and BMs, while shear stresses in members were evaluated based on SFs. Figure 7 shows the largest AFs, BMs and SFs of the cladding support members obtained from time-history analyses. In the figure, the member number is given in the order of the largest effects. Comparison of Fig. 7(a) and Fig. 7(b) shows that BMs had a more remarkable effect on

the axial stresses for members along the length direction than for members along the span direction. Correspondingly, AFs had a more remarkable effect on the axial stresses for members along span direction than for members along the length direction. Shear stresses due to SFs were more remarkable for members along the length direction.



(a) Largest load effects (AF, BM and SF) of cladding support members along length direction
(b) Largest load effects (AF, BM and SF) of cladding support members along span direction
Figure 7. Comparison of largest AFs, BMs and SFs obtained from time-history analyses of cladding support members.

4.3 Contribution ratios for largest member stresses

The displacements $\{D(t)\}$ in Eq. (2) of the support points connecting the main structural frame and the cladding support members were also obtained during the time-history analyses of the completed FE model. Only the FE model of cladding support members was used to obtain the $\{R\}$ in Eq. (2), under constraint conditions consistent with those in the completed FE model. The member stresses due to overall wind effects can be obtained with the known $\{R\}$ and $\{D(t)\}$, as mentioned in Sec. 2.

The contribution ratios of overall wind effects and local wind effects for the largest member stresses are defined by:

$$\gamma_o = \frac{\hat{r}_o}{\hat{r}}, \quad \gamma_l = 1 - \gamma_o = 1 - \frac{\hat{r}_o}{\hat{r}}. \quad (7)$$

Here, γ_o and γ_l are the contribution ratios of overall wind effects and local wind effects respectively. $\hat{r}$, $\hat{r}_o$ represent the actual largest load effect and the largest load effect due to the overall wind effects only, which were focused on the member stresses (maximum and minimum member stresses).

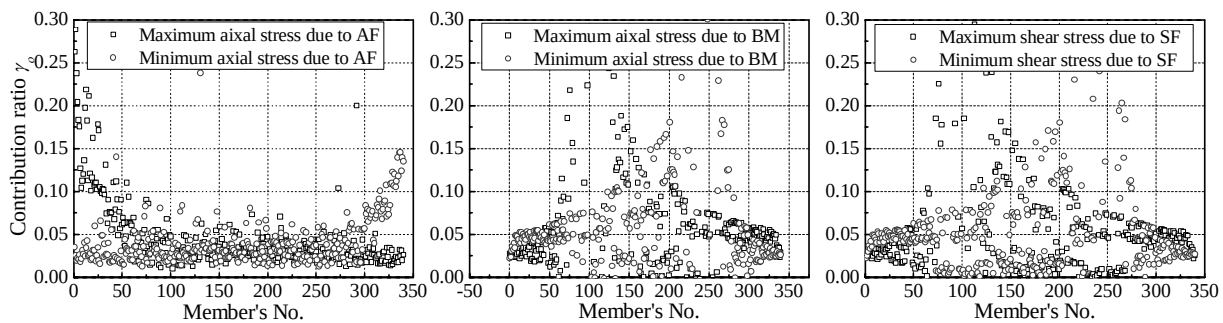


Figure 8. Contribution ratios of overall wind effects for the largest member stresses of members along length direction

Contribution ratios of overall wind effects for the largest member stresses of members along length direction are shown in Fig. 8. As in Fig. 7, the member number is given in the order of the largest effects obtained from the time-history analyses in Fig. 8. The contribution ratios of overall wind effects for the largest member stresses were less than 0.15 for most cladding support members. This means that current wind load codes are not so bad for most cladding support members, which don't take account of the contribution of overall wind effects for largest member stresses. However, the contribution ratio γ_o can be larger than 0.15 for several members and the largest value of γ_o was about 0.3, also shown in Fig. 8. Considering only the contribution of local wind effects for such members would remarkably underestimate the largest member stresses.

5 CONCLUDING REMARKS

Internal stresses in cladding support members of long-span arched roofs under wind load were investigated by time-history analyses of the completed FE model, including main structural frame and cladding support members. Contributions of overall wind effects and local wind effects to the largest member stresses were discussed:

- 1) The displacements of the supporting points connecting the main structural frame and cladding support members were assumed to represent the overall wind effects of the long-span roof structure.
- 2) Cladding members stresses due to the overall wind effects were evaluated by a quasi-static method.
- 3) The contribution ratios of overall wind effects to the largest member stresses were less than 0.15 for most cladding support members. However, there were members for which the contribution ratio can be larger than 0.15 and the largest value was about 0.3. Considering only the contribution of local wind effects to such members would remarkably underestimate the largest member stresses.

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7 REFERENCES

- 1 Uematsu, Y., Yamada, M., Inoue, A., Hongo, T., Wind loads and wind-induced dynamic behavior of a single-layer lattice dome, *Journal of Wind Engineering and Industrial Aerodynamics* 66 (1997), 227-248.
- 2 Uematsu, Y., Kuribara, O., Yamada, M., Sasaki, A., Hongo, T., Wind-induced dynamic behavior and its load estimation of a single-layer latticed dome with long span, *Journal of Wind Engineering and Industrial Aerodynamics* 89 (2001), 1671-1687.
- 3 Nakayama, M., Sasaki, Y., Matsuda, K., Ogawa, T., An efficient method for selection of vibration modes contributory to wind response on dome-like roofs, *Journal of Wind Engineering and Industrial Aerodynamics* 73 (1998), 31-43.
- 4 Li, Y.Q., Tamura, Y., Yoshida, A., Katsumura, A., Cho, K., Wind loading and its effects on single-layer reticulated cylindrical shells, *Journal of Wind Engineering and Industrial Aerodynamics* 94 (2006), 949-973.
- 5 Zhou, Y., Kareem, A., Gust loading factor: new model. *J. Struct. Eng., ASCE* 127 (2001), 168-175.
- 6 Holmes, J.D., Effective static load distributions in wind engineering, *Journal of Wind Engineering and Industrial Aerodynamics* 90 (2002), 91-109.
- 7 Katsumura, A., Tamura, Y., Nakamura, O., Universal wind load distribution simultaneously reproducing largest load effects in all subject members on large-span cantilevered roof, *Journal of Wind Engineering and Industrial Aerodynamics* 95 (2007), 1145-1165.
- 8 AIJ-RLB, 2004. *AIJ Recommendations for Loads on Buildings*. Architectural Institute of Japan.
- 9 American Society of Civil Engineers, 2010. *ASCE Standard ASCE/SEI 7-10, Minimum Design Loads for Buildings and Other Structures*. Reston, Virginia, USA.
- 10 Australian/New Zealand Standard, 2002. *Structural design actions, Part 2: wind actions*, AS/NZS 1170.2.
- 11 Yoshida, A., Tamura, Y. and Kurita, T., Effects of bends in a tubing system for pressure measurement, *Journal of Wind Engineering and Industrial Aerodynamics* 89 (2001), 1701-1716.
- 12 Li, Y.Q., Tamura, Y., Equivalent static wind load estimation in wind-resistant design of single-layer reticulated shells, *Wind and Structures*, 2005, 8 (6), 443-454.