**Wind Loads Acting on Clad Scaffolding**

**F. Wang1, Y. Tamura2 and J.W. Li1**

**1**School of Highway

Chang’an University, Xi’an 710064, China

2School of Civil Engineering

Beijing Jiaotong University, Beijing 100044, China

**Abstract**

Safety is the most important issue in civil engineering construction. Cladding may cause severe wind loads acting on scaffolding, especially when it is nonporous. This study aims to investigate aerodynamic characteristics on clad scaffolding. Wind tunnel experiments were carried out based on a prototype of scaffolding with nonporous cladding. Various scaffolding geometries, building openings and neighbouring building conditions were considered. Aerodynamic force coefficients were determined based on experimental data. Comparisons were made between experimental data and current related design recommendations. Tie members mainly contribute to the horizontal stability of scaffolding and prevent scaffolding from collapse. Wind loads acting on scaffolding tie members, gust loading factors and interference factors were calculated as well. Based on this study, wind-resistant design considerations for scaffolding were proposed.

**Introduction**

Scaffolding is a temporary structure used to support people and material during construction or maintenance of buildings and other large structures. Such temporary support systems are widely used because they are economical, convenient and have a wide range of adaptability. Safety is the most important issue in civil engineering construction. Ohdo[1] investigated scaffolding collapse accidents and found that about 10% of severe collapse accidents were due to wind. Irtaza et al.[2] investigated models of sheet-clad and elevated sheet-clad scaffolding surrounding a cubic building. Experimental data and code recommendations were compared. Wang et al.[3] investigated wind loads acting on nonporous clad scaffolding with six scaffolding geometries and four building opening ratios. According to the literatures, clad scaffolding may suffer more severe wind loads because of the cladding, especially when it is nonporous. Existing design recommendations provide limited information on wind loads on clad scaffolding. This study aims to investigate aerodynamic characteristics of clad scaffolding. Wind tunnel experiments were carried out based on the prototype of the scaffolding with nonporous cladding. A systematic study on wind load characteristics of clad scaffolding with different arrangements, building opening ratios and neighbouring building conditions were conducted.

**Experimental setup**

Wind tunnel experiments were carried out in a Boundary Layer Wind Tunnel in Tokyo Polytechnic University, Japan. The atmospheric boundary layer was simulated as a geometrical scale of 1:75. Open terrain characteristics were simulated and a velocity scale of 1:2.5 was adopted. The power law exponent α of mean wind speed was 0.2. The mean wind speed at the reference height zref (top of the principal building, which is 318mm above the bottom of the tunnel) was around 8.6m/s and the corresponding turbulence intensity was approximately 21%.

The prototype dimensions of the building were 19.2m×12m in plan and 23.8m in height. The scaffolding was assembled by using typical door-type tubular-steel scaffold units 1.7m high, 0.9m wide and 1.8m in span (one-bay). The prototype scaffolding was 27.2m high, and 3.4m (two-stories) higher than the principal building. The distance between the building surface and the cladding of the scaffolding was 1.2m in full scale. Nonporous acryl models 5mm thick were made to simulate the nonporous clad scaffolding (scaffolding pipes were ignored). Pressure taps were fixed symmetrically on both the outer and inner surfaces of the scaffolding models. 188 pressure taps were fixed on scaffolding model L, which was placed along the long side of the building. 116 pressure taps were fixed on scaffolding model S, which was placed along the short side of the building, as shown in Figure 1. In this study, twelve scaffolding geometries were tested, and there was only one measuring scaffolding model in each geometry. The last letters of the geometry definitions stand for the measuring model.

|  |
| --- |
|  |
| (a) IL (b) IS (c) IIL (d) IIS |
|  |
| (e) LL (f) LS (g) UL (h) US |
|  |
| (i) CL (j) CS (k) OL (l) OS |
| Figure. 1 Definitions for angle and scaffolding geometries (top view). |

The experimental principal buildings were made from organic glass. To simulate the internal wind environment of the building under construction, floor slabs and pillars were considered, and each floor slab had a hole representing the stairwell. Principal building opening ratios (*ΦB*) were 0%, 20%, 40%, 80%, as shown in Figure 2.

|  |  |  |  |
| --- | --- | --- | --- |
|  | | | |
| (a) Building opening ratio (*ΦB*) 0% | (b) Building opening ratio (*ΦB*) 20% | (c) Building opening ratio (*ΦB*) 40% | (d) Building opening ratio (*ΦB*) 80% |
| Figure 2 Principal building models (unit: mm). | | | |

Three scaffolding geometries (IL, LL and OL) were tested in the study of the interference effects of a neighbouring building on wind loads on scaffolding. The neighbouring building model had the same dimensions as the principal building.

Wind tunnel setup and experimental models are shown in Figure 3.

|  |  |
| --- | --- |
|  |  |
| (a) Geometry UL, opening ratio 40%, isolated building. | (b)Geometry IL, opening ratio 0%, with neighboring building |
| Figure 3 Wind tunnel setup and experimental models | |

Pressure coefficients were obtained at a sampling frequency of 781Hz using a multi-channel simultaneous-scanning pressure measurement system. For each case, ten 20s-long samples were collected, which corresponded to 26Hz and ten 10min-long samples in full scale. Wind direction (θ) was changed at intervals of 5°, except the cases with a neighbouring building in which the wind direction was changed every 15°. The tubing effects were compensated by the gain and phase-shift characteristics of the pressure measuring system.

**Results and Discussions**

In this study, Mean and area-averaged wind force coefficients for scaffolding were studied, largest peak tensile forces in tie members were estimated and interference factors were determined. Based on the wind tunnel experimental data and analysis results, equivalent static wind load acting on scaffolding was be proposed by using the equation:

 (1)

where *qH* is the velocity pressure at a reference height *H*, *A* is the reference area, *C* is aerodynamic force coefficient, *G* is gust loading factor and *IF* is the interference factor.

In this study, the aerodynamic force coefficient, gust loading factor and interference factor will be discussed, respectively.

*Aerodynamic force coefficient*

Most design recommendations provide an aerodynamic force coefficient or wind force coefficient for scaffolding for wind loads calculation. Usually uniform coefficient will be given for entire scaffolding. BS EN 12811[4] (2003) states that the aerodynamic force coefficient for the cladding shall be assumed as 1.3 for perpendicular direction. JGJ 128[5] (2000) provides a shape coefficient of wind loads by considering a solidity ratio of cladding and principal building openings. If the principal building has wall openings, the shape coefficient of wind load shall be 1.3*φ*, where *φ* is the solidity ratio of the scaffolding. For nonporous cladding, it will be 1.3.

Table 1 shows the largest positive and negative mean panel force coefficients of all wind directions and building opening ratios for different scaffolding geometries. Mean panel force coefficients for many scaffolding geometries exceed the value of 1.3 which provided by BS EN 12811 and JGJ 128.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Scaffolding  geometry | IL | IIL | LL | UL | CL | OL | IS | IIS | LS | US | CS | OS |
|  | 1.52 | 1.51 | 1.39 | 1.20 | 1.51 | 1.48 | 1.45 | 1.38 | 1.34 | 1.33 | 1.11 | 1.19 |
|  | -1.02 | -0.70 | -1.57 | -1.19 | -1.43 | -0.19 | -1.00 | -0.74 | -1.65 | -1.49 | -1.08 | -0.08 |

Table 1 Largest positive and negative mean panel force coefficient for different geometries

SCEA recommendation[6] (Japanese Guideline) suggests shape compensation factor and position compensation factor for mean wind force coefficient for clad scaffolding. Without regard to the position compensation factor, mean panel force coefficient for the scaffolding models in this study are calculated by using the method from SCEA recommendation, which are around 1.26 and 1.3 for scaffolding model L and scaffolding model S, respectively. The position compensation factor is a kind of consideration of scaffolding geometry. SCEA recommendations provide the position compensation factor for positive and negative mean wind force coefficient separately. The position compensation factors for the positive wind force coefficients are larger than 1 and can be up to 1.31, so that the mean panel force coefficient suggested by SCEA recommendation for the scaffolding models in this study can be up to 1.7 for some area on scaffolding. However, the position compensation factors for the negative mean wind force coefficients are not larger than 1. Therefore, the negative mean panel force coefficient for the scaffolding models in this study are mostly smaller than 1.3, also smaller than the results from wind tunnel experiment.

The aerodynamic force coefficient for scaffolding suggested by those design recommendations seems inadequate and rational increment will be needed for calculating design wind loads. Clad scaffolding is widely used in engineering constructions, a proper recommendation of aerodynamic force coefficient is needed and more safety consideration should be taken into account. Based on the data of all experimental cases, the largest positive and negative mean panel force coefficient are better to be larger than 1.6 and -1.7.

SCEA recommends area-averaged force coefficients for different scaffolding zones. Comparisons between the recommended values and experimental data were also made. Based on the experimental data, the largest positive area-averaged wind force coefficient for the top zone is 1.6 larger than the value 1.3 recommended by SCEA recommendations. The largest negative area-averaged wind force coefficients for the top zone, side zone and middle zone are -1.4, -1.9 and -1.7 larger than the values -1.3, -1.3 and -0.8 recommended by SCEA recommendations, respectively. Comparison of largest area-averaged force coefficients between experimental data and SCEA recommendations is shown in Table 2.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Zone of scaffolding | Experimental data | SCEA recommendations |
| Largest positive area-averaged force coefficient | Top | 1.6 | 1.3 |
| Middle | 1.6 | 1.7 |
| Side | 1.5 | 1.7 |
| Largest negative area-averaged force coefficient | Top | -1.4 | -1.3 |
| Middle | -1.7 | -0.8 |
| Side | -1.9 | -1.3 |

Table 2 Comparison of largest area-averaged force coefficient between experimental data and SCEA recommendations

*Gust loading factor*

Peak tensile forces in tie members were estimated in this study. The gust loading factors were determined by using the following equation:

 (2)

where  is the largest peak tensile force among all tie members, which estimated by pressure integration. Three kinds of tying pattern of scaffolding ties are calculated in this study. Each tie member is corresponding to two scaffold units, four scaffold units and six scaffold units. Two scaffold units represent one tie for one-bay-two-stories scaffolds. Four and six scaffold units represent one tie for two-bays-two-stories scaffolds and three-bays-two-stories scaffolds, respectively.

The reference areas are considered as every two scaffold units, four scaffold units and six scaffold units, respectively, and the design wind speed at the reference height (building top) is 21m/s.The aerodynamic force coefficient for entire scaffolding is 1.7 which is the largest value from the experimental data.

|  |
| --- |
|  |
| Figure 4 Largest gust loading factor for different scaffolding geometries and reference areas. |

For each scaffolding geometry, the largest gust loading factor is picked out among all wind directions and all building opening ratios as shown in Figure 4. The largest gust loading factors for 2 scaffold units are always larger than for 4 and 6 scaffold units. The largest gust loading factor tends to be smaller when the reference area increases.

|  |
| --- |
|  |
| Figure 5 Largest gust loading factor for different scaffolding geometries. |

Figure 5 shows the largest gust loading factor among all wind directions, all building opening ratios and all reference areas for different scaffolding geometry. As discussed in Figure 4, the largest gust loading factors are always found for the reference area of 2 scaffold units. The largest value of all is 4.1 which is found for geometry IIS. The values for geometries UL, CS, OL and OS are quite small compare to other geometries, which are around 2.5~2.7. Geometries UL, CS, OL and OS have the same feature that both two side edges of the measured scaffolding are covered by the scaffolding placed at the adjacent building sides.

*Interference factor*

Interference effects of neighbouring building on peak tensile forces in ties were studied, interference factors were determined. For wind-resistant design consideration, the peak tensile forces in tie members should include interference effects by multiplying the interference factor (*IF*). The distributions of interference factors are shown in Figure 6, 7 and 8. The numbers nearby the dots are the values of *IF*.

For different scaffolding geometries, the largest interference factors are found when the neighbouring building is located in front of the scaffolding for a building distance 1.5 times the building depth. When the neighbouring building is located on the left or right side of the measured scaffolding, the interference factors are always larger than 1.

The Neighbouring building has less effect on the wind direction which causing the largest peak tensile force. The largest peak tensile force among all tie members is usually occurs at the side edge of scaffolding.

|  |
| --- |
|  |
| Figure 6 Distributions of interference factors, geometry I. |

|  |
| --- |
|  |
| Figure 7 Distributions of interference factors, geometry L. |

|  |
| --- |
|  |
| Figure 8 Distributions of interference factors, geometry O. |

**Conclusions**

(1) Based on the data of all experimental cases, the largest mean panel force coefficient is 1.7 which is larger than 1.3 recommended by BS EN 12811 and JGJ 128. In this study, the largest positive area-averaged wind force coefficient for the top zone is 1.6 larger than the value 1.3 recommended by SCEA recommendations. The largest negative area-averaged wind force coefficients for the top zone, side zone and middle zone are -1.4, -1.9 and -1.7 larger than the values -1.3, -1.3 and -0.8 recommended by SCEA recommendations, respectively.

(2)The neighbouring building has significant effects on wind loads acting on scaffolding. For different scaffolding geometries, the largest interference factors are found when the neighbouring building is located in front of the scaffolding for a building distance 1.5 times the building depth. When the neighbouring building is located on the left or right side of the measured scaffolding, the interference factors are always larger than 1.

(3) Wind-resistant design considerations are discussed in this study and equivalent static wind load acting on scaffolding is proposed. Aerodynamic force coefficient, gust loading factor and interference factor are investigated. If the scaffolding is covered with nonporous cladding or high solidity ratio cladding, the current design recommendations may underestimate the wind loads acting on clad scaffolding.

**Acknowledgments**

This study was funded by the Ministry of Education, Culture, Sports, Science and Technology, Japan, through the Global Centre of Excellence Program, 2008-2012, which is gratefully acknowledged, and was supported by “the Fundamental Research Funds for the Central Universities（310821161019）”.

**References**

1. Ohdo, K., Takanashi, S., Hino, Y., Saito, K., Measurement of wind load acting on the scaffolds, *Specific Research Reports of the National Institute of Industrial Safety*, 2005, NIIS-SRR-NO.31(In Japanese).
2. Irtaza, H., Beale, R.G., Godley, M.H.R., A wind-tunnel investigation into the pressure distribution around sheet-clad scaffolds, *Journal of Wind Engineering and Industrial Aerodynamics*, 103, 2012, 86-95.
3. Wang, F., Tamura, Y., Yoshida, A., Wind loads on clad scaffolding with different arrangements and building opening ratios. *Journal of Wind Engineering & Industrial Aerodynamics*, 120, 2013, 37–50.
4. British Standards Institution, BS EN 12811-1, Temporary Works Equipment – Part 1: Scaffolds – Performance Requirements and General Design, 2003.
5. The Ministry of Construction of People’s Republic of China, JGJ 128, Safety and technical code for frame scaffolding with steel tubules in construction (in Chinese), 2000.
6. Scaffolding and Construction Equipment Association of Japan, Safety technical guideline for scaffolding to wind loads (in Japanese), 1999.