

Temporary Structures in Shanghai EXPO2010

– Structural Design Specification and Example

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Abstract

Many temporary buildings and structures are constructed in the Expo Park, Shanghai as pavilions and facilities of EXPO2010. New materials and new structural systems are expected to be used and appear. The structural design specification for temporary structures of EXPO2010 is summarized and the structural design of Norwegian pavilion is described in this paper.

Keywords: temporary structures, EXPO, structural design, pavilion, PTFE yarn fabric

1. Introduction

Except several permanent buildings and structures, most pavilions, built for Shanghai EXPO2010, are temporary structures. Three types of pavilions are available for participants. Type 1 is self-build pavilion, which is designed and built by the participant himself on a plot allocated by the organizer. Type 2 is rental pavilion, which is a stand-alone pavilion built by the organizer and rented to participants. Type 3 is joint pavilion, which is constructed by the organizer and allocated to developing countries free of charge [1].

Area of plot for self-build pavilion is 1000m² to 6000m². Total floor area of self-build pavilion shall not exceed the plot area and height shall not exceed 20m. In order to encourage and help for foreign participants to design and build pavilions by themselves, the Design Standard for Temporary Buildings and Structures of the World Expo is prepared in both Chinese and English versions [2]. The design standard contains architectural section, structural section, and another seven sections which relate to design of water supply, drainage, etc.

In the structural section of the design standard, special specifications are described on general principle of structural design, design loads, seismic design, steel structures, aluminum alloy structures, cable structures, membrane structures, timber structures, subgrade and foundation..

In this paper, the structural design specification for temporary structures in EXPO2010 is summarized at first. Then, Norwegian pavilion of timber structure with membrane roof, is introduced.

2. Structural design specification for temporary structures of EXPO2010

2.1 Principle of structural design

The structural design specification is prepared for structural design of temporary structures to be built in the Shanghai Expo Park area as pavillions or facilities used for EXPO2010. Temporary structures should meet provisions shown below, in principle;

- 1) The maximum storey is limited to 4 and height shall be less than or equal to 20 meters.
- 2) Underground floor shall not be constructed.
- 3) Building materials that can be reused or recycled after the EXPO, are recommended to be used for pavillions and facilities.. Light-weight materials, such as steel, building membrane, aluminum alloy, timber, are recommended in the specification. Use of concrete is restricted. It is allowed only for composite slab and foundation.
- 4) The EXPO will last six months. Temporary structures in Expo Park will be removed after the expiration of the period. Considering the period of preparation and closing works before and after the EXPO, the design working life for temporary structures is assumed one year in the specification. When any of temporary structures need to be used further for any special reason, re-justification, review and approval shall be requested.

In the Chinese code, “Unified Standard for Reliability Design of Building Structures” (GB50068-2001) [3], the design reference period is 50 years, which is the recurrence interval to be assumed in determining variable actions (loads) and values for time-dependent material properties. The statistic parameters of loads provided in the code, “Load Code for the Design of Building Structure” (GB50009-2001) [4] are based on this design reference period (50 years). All structures including permanent and temporary structures have to take 50 years as design reference period in order to use loads and material properties determined in related codes. Structural importance coefficient γ_0 is used to modify design loads corresponding to importance and design working life of structures. For example, γ_0 is 0.9 for temporary structures.

Sufficient reliability of structures has to be kept during design working life. That is to say, structures shall maintain good working performance, sufficient durability and overall stability for design working life. The reliability is ensured through the limit state design method, which is based on probability theory, and is used nowadays in Chinese design codes.

“Unified Standard for Reliability Design of Building Structures” (GB50068-2001) [4] requires to consider two limit states in structural design. They are ultimate limit state and serviceability limit state. In the ultimate limit state, structural frames or members have reached load bearing capacities or they can no longer bear loads because they had suffered serious damages such as overturning, buckling and other types of instability. Once the ultimate limit state occurs, structures will not be safe for continuous use. On the other hand, when structural frames or members reach the serviceability limit state, normal function of structures will not be available, though structures can bear loads and structural safety is assured. In serviceability limit state, for example, unusual deformation, vibration or cracks are observed and normal function for use is lost. Different load combinations shall be assumed in structural design in order to meet the requirements related to these two limit states. Design equations for ultimate limit state and serviceability limit state are written as

$$\gamma_0 S \leq R \text{ (for ultimate limit state)} \quad (1)$$

$$S \leq C \text{ (for serviceability limit state)} \quad (2)$$

where γ_0 is structure importance coefficient, S is design value of the effect of action, R is design value of the resistance of member, C is allowable value (deformation, crack, etc.) relating to normal function of use.

Structure importance coefficient of the temporary structures in Expo Park is 0.9 in the specification. Load combinations, partial factors for combinations and resistance partial factors provided in the specification have come from the Load Code and other structural design codes used in China nowadays.

2.2 Loads and seismic design

Loads are classified into three categories: permanent loads (dead load, prestress, etc.), variable loads (live load, snow load, wind loads, etc.) and accidental loads (shock, explode, etc.). Different probability models are defined for each category of loads. Based on these models, exemplary values for structural design loads are determined corresponding to a design reference period (recurrence interval, 50years). Combination of loads, such as variable loads plus permanent loads, shall be considered in structural design. Nominal values of loads, partial factors and combination factors necessary in the load combination are given in the national load code “Load Code for the Design of Building Structure” (GB50009-2001) [4].

Loads provided in the specification of temporary structures for EXPO have come from the national load code GB50009-2001 applied to the location of Shanghai city. Reference snow load in Shanghai is 0.2kN/m^2 , which corresponds to recurrence interval of 50 years, and is calculated using annual maximum snow drift data observed at a flat open ground in Shanghai. Reference velocity pressure of wind in Shanghai is 0.55kN/m^2 , which corresponds to recurrence interval of 50 years, and is calculated from the annual maximum 10-minute-average wind speed observed at height of 10m above a flat open ground..

Seismic design shall be carried out for the temporary structures. Performance requirements for seismic design is that structural frame shall not be damaged or can be continuously used without repair after suffering a frequently encountered earthquake. When suffering an

earthquake of design seismic intensity, structures shall not collapse or life safety shall be guaranteed even when they suffer serious damage. According to the importance of service and functions, temporary structures are classified into three categories of B, C and D. Seismic design requirements differs depending on the category [5].

Seismic intensity grade for the Expo Park is 7. In seismic design, design seismic acceleration of ground motion is 0.10g, while design characteristic period of ground motion of the site is 0.9s for a frequently encountered earthquake.

2.3 Structural systems

Light weight structures made of steel, aluminum alloy, cable, membrane and timber are recommended to be used as temporary structures for the EXPO. New materials and advanced structural systems are expected.

Detailed description on property of materials, structural systems, structural analysis, design of structural members and connections, etc., are provided in the specification by summarizing the current Chinese design codes.

2.4 Others

Subgrade and foundation shall be designed properly corresponding to ultimate limit state and serviceability limit state. Requirements relating to materials, natural foundations, shallow foundation and pile foundation have been stated in details in the specification. For soil improvement works, not only the bearing capacity of foundation shall be calculated for ultimate limit state, but also the deformation should be verified for serviceability limit state.

3. A temporary structure in EXPO: Norwegian pavilion

3.1 Outline

The Norwegian pavilion is a timber structure with membrane roof (Figure 1). It will be constructed by using glued-laminated timber elements made in Norway. Materials for roof membrane and other supplemental parts will be supplied in China.

Main structure of the pavilion is composed of fifteen independent tree-like structures. Every "tree" has four chamfered arms at the top of stem and trees are connected with each other at ends of four arms. The roof is covered with a new kind of architecture fabric, the PTFE yarn fabric.

The floor area of Norwegian pavilion is approximately 1765m² consisting of a visiting area, a restaurant and a business centre. Design of the pavilion is carried out by Team Helen&Hard Architects (Norway) and SHZF Architectural Design Co., Ltd (local design institute). Tongji University is cooperating with SHZF as a structural design adviser.



Figure 1: Schematic perspective of Norwegian pavilion

3.2 Material and structural system

PTFE yarn fabric coated with fluoropolymer used as roof material is developed by GORE. This new architectural fabric, named TENARA, is much more flexible compared with coated fiberglass or PVC fabrics. Also, this fabric has good flame resistance, high light transmission and, in addition, it can be recycled. Thickness of the fabric used in Norwegian pavilion is 0.55mm and tensile strength for both warp and fill direction is 4kN/5cm.

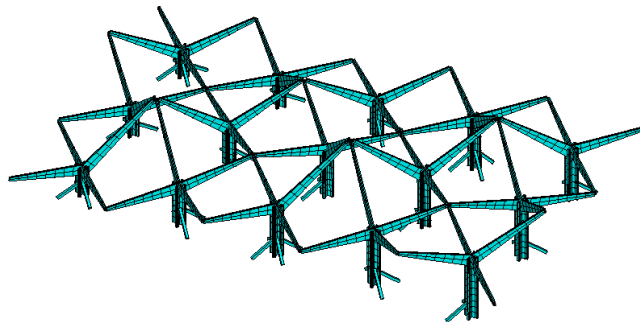
Polyester belts are used as cables to reinforce the membrane and to form membrane edges. Tree structures are made of glulam timber manufactured in Norway in accordance with Euro-code. The tree members are prefabricated in Norway and shipped to China for construction.

The Norwegian EXPO pavilion can be divided into two parts; one is timber frame (tree structure) and the other is membrane roof as shown in Figure 2. Pavillion roof is about 56.5m long and 33.9m wide. Roof membrane surface consists of four point sails (four edge belts form one sail) and eyelet membrane (the part between two sails) as shown in the figure.

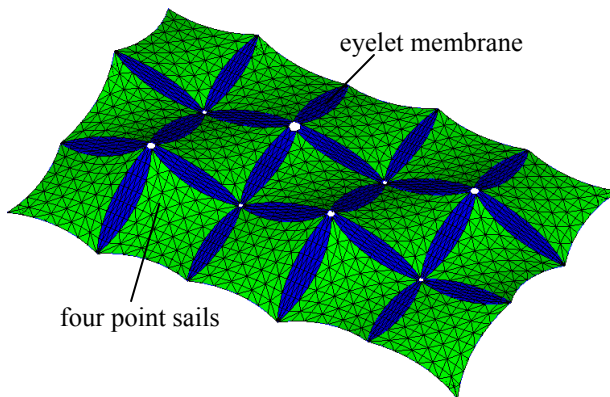
3.3 Loads and load combinations

Loads assumed in membrane roof design are dead load, pre-tension of membrane and belt, wind load, snow load and live load. Pre-tension for 4 point sail membrane is 1.0kN/m, while pre-tension for eyelet membrane is 0.5kN/m. Pre-tension introduced in edge belts varies from 8kN to 24kN.

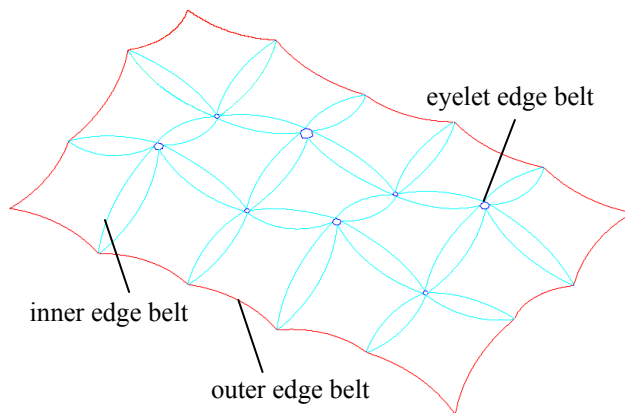
Wind load is calculated according to the specification for the temporary and the national load code. Wind pressure is 0.55kN/m² and the wind pressure coefficient comes from the load code. Live load of 0.3kN/m² should be considered in structural design, which is larger than snow load of 0.2kN/m². Snow load need not be included in load combination, so it is only used for checking the ponding phenomenon.



(a) timber frame



(b) main membrane roof



(c) belts as cables

Figure 2: Structural system of Norwegian pavillion

Table 1 shows twelve cases of loading condition and the partial factors (combination coefficients) for membrane and cable design. Wind1, wind2 and wind3 correspond to wind pressure patterns representing suction, pressure and local distribution, respectively. Loading cases LC1-6 are used to check the strength of membrane and belts while loading cases LC7-10 are used for maximum displacement examination. Water flow on the roof surface is examined in loading cases LC11-12, supposing conditions of normal use and snow drift.

Seismic design is not necessary for membrane roof, but it is carried out for the timber frame of the pavilion.

Table 1: Load combination and partial factor

	Load case	Dead load	Pre-tension	Live load	Wind1	Wind2	Wind3	Snow
Long term combination	LC1	1.2	1.0					
	LC2	1.2	1.0	1.4				
Short term combination	LC3	1.0	1.0		1.4			
	LC4	1.0	1.0				1.4	
	LC5	1.2	1.0	1.4		0.84		
	LC6	1.2	1.0	0.98		1.4		
Displacement check	LC7	1.0	1.0	1.0				
	LC8	1.0	1.0		1.0			
	LC9	1.0	1.0	1.0		0.6		
	LC10	1.0	1.0	0.7		1.0		
Ponding check	LC11	1.0	1.0					
	LC12	1.0	1.0					1.0

3.4 Structural analysis and design

The structural analysis and design are independently carried out by engineers of Norway side and Chinese side.

Initial geometry of the roof is obtained by means of shape finding analysis. Then, loading cases in Table 1 are used for stress analysis. From Eq.(1), Eq.(3) and Eq.(4) are written for membrane and belt check.

$$\sigma_{\max} \leq \frac{f_k}{\gamma_R} \cdot \frac{1}{\gamma_0} \quad (3)$$

$$N_{\max} \leq \frac{P}{\gamma_R} \cdot \frac{1}{\gamma_0} \quad (4)$$

where σ_{max} and N_{max} are the maximum stress of membrane and the maximum tension of belt for every load case LC1-6, f_k and P are the normal values of the tensile strength of membrane and belts, γ_R is the resistance partial factor of membrane and belts. γ_R is 7.0 for long term load combination and 3.5 for short term load combination according to the specification for temporary structures. In this project, the same value of γ_R is used for both membrane and belts considering the belts are Polyester material.

From load cases LC7-10, the maximum displacement is calculated for every load case and the ratio of displacement to span is examined (the ratio should be smaller than 1/15).

Figures 4-6 show some results from analysis.

4. Conclusions

World EXPO is one of the biggest exhibition event in the world, which provides architects and structural engineers with a good opportunity for creating new buildings and structures. Besides Norwegian pavilion, many attractive pavilions are going to be designed and constructed. Remarkable technical achievements are expected on the future of temporary structures.

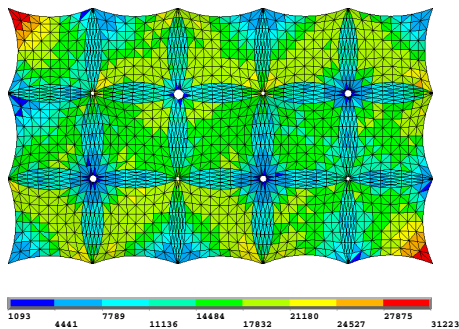


Figure 4: Membrane stress of LC3

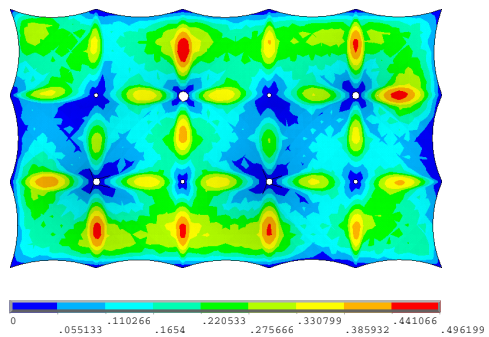
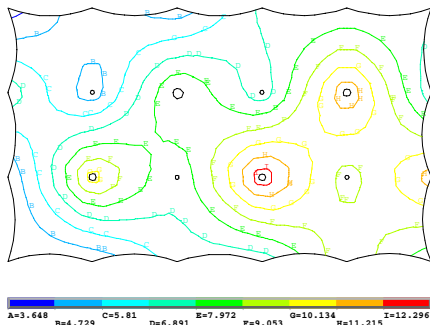
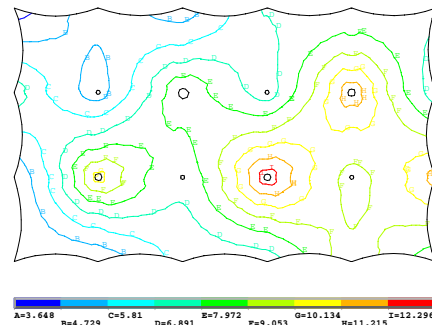


Figure 5: Membrane displacement of LC7



(a) LC11



(b) LC12

Figure 6: Contour map of membrane surface

Acknowledgements

Team Helen& Hard Architects and SHZF Architectural Design Co., Ltd are appreciated for providing Norwegian Pavilion information in preparing this paper. Dr Tatsuo Murota, who is the chair of WG19 of IASS, gives the authors many valuable suggestions in writing this paper. Dr Tatsuo Murota is greatly appreciated.

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