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Structural design loads on temporary spatial structures

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Abstract

In this paper, the issue of design load on reduction in the structural design of temporary spatial structures is discussed using risk analysis tools. In chapter 2, actions due to loads are classified into two categories from the viewpoint of occurrence prediction. In addition, it will be shown that, when assuming target levels for design loads in structural design of spatial structures, both ordinary economic loss and loss of priceless possessions including human life have to be considered. Chapter 3 shows that; 1) reduction of design loads has economic advantage and leads to better cost performance in the range of shorter working years, 2) on the other hand, risk to priceless possessions and human lives in TSS are far bigger than that in ordinary spatial structures, and in order to reduce the risk to those in TSS, occurrence probability of safety limit load for TSS has to be reduced to the same level as for ordinary structures. In chapter 4, introduction of the safety control system is investigated for reducing structural design loads.

Keywords: temporary spatial structure, structural design load, damage limit, safety limit, variable action, accidental action, expected total cost, expected death, safety control system, temporary countermeasure.

1. Introduction

Temporary spatial structures (hereinafter TSS) such as EXPO pavilions have been used for a short period of time. However, loads assumed in structural design of TSS are not so small compared with those assumed in ordinary spatial structures. Many engineers think that design loads for TSS ought to be far smaller corresponding to the short period of use. Nevertheless, they haven’t been able to find reasons to justify the thought. In this paper, the issue of design load reduction for TSS will be discussed using risk analysis tools.

On the other hand, there have been known many ideas for reducing load effects at hazardous conditions; for example, prevention of collapse by setting extra guy ropes in stormy conditions, strengthening of roof by adding extra supports in deep snow, etc. If we provide spatial structures with such extra subsystems, and can prevent damage or collapse, design load reduction will be acceptable. In this paper, relation between such extra subsystems and design load reduction will also be discussed.

2. Preliminary discussions

2.1. Ultimate limit state and serviceability limit state

In this study, two states of structures will be considered in accordance with ISO2349 [1]. One is the ultimate limit state. This is a state, where a structure is subjected to a load called as safety limit load and suffers collapse or serious structural damage. The other is the serviceability limit state. This is a state, where a structure is subjected to a load called as damage limit load, and suffers damage to structural members, services, functions, etc. And the damage to structure may also reduce the load bearing capacity of the structure at ultimate limit state. Once a structure experiences this state, it cannot be used again without repairing.

2.2. Occurrence prediction of loads

Loads are classified into the following two categories from the viewpoint of occurrence prediction.

Category 1: Loads, the occurrence time of which can be predicted beforehand, and allows enough time for the owner of structure to prepare temporary countermeasures necessary for preventing possible damage by the predicted time. They are called as variable loads, and include live loads, snow loads, wind loads, etc.

Category 2: Loads, the occurrence time of which cannot be predicted beforehand, and so the owner of structure cannot take any temporary countermeasures for preventing possible damage. They are called as accidental loads, and include earthquakes.

2.3. Economic loss of damage

Collapses of buildings and damage to structures are economic loss that can be got back by rebuilding or repairing. Spatial structures are, in general, planned to produce most appropriate cost performance. So, design levels of loads are assumed taking the cost performance into consideration, and, as a result, expected economic losses are estimated.

However, damage to priceless treasures such as national heritage, for example, cannot be recovered, and the loss of such damage cannot be estimated. Therefore, possible best countermeasures to prevent such loss should be supplied. Even though loss of human life can be estimated as an economic loss, it is required, in some cases, to treat the loss as an equivalent to priceless treasure.

Therefore, when assuming target levels for design loads in structural design of spatial structures, both ordinary economic loss and loss of priceless possessions including human life have to be considered.

3. Risk analysis

3.1 Economic risk

When examining the cost performance of construction, expected total cost (ETC) is often referred to as a measure for judgment (see Mori [2]). ETC is expressed by summation of initial cost and expected cost for loss due to collapse and damage, as shown in equation (1).

$$Ct = Ci + n \cdot (Ps \cdot Ci + Pd \cdot Cr) \tag{1}$$

where Ct : expected total cost

Ci : initial construction cost

Cr : expected repairing cost

Ps : occurrence probability of safety limit load

Pd : occurrence probability of damage limit load

n : design working year of structure

Initial construction cost has a close relation with structural design loads. Here we try to calculate ETC for an ordinary spatial structure and a TSS.

We assume following values for an ordinary spatial structure;

Ci: 1,000,000 euros
Ps: 0.2 %
Pd: 1%
Cr: 100,000 euros (=1/10 of initial construction cost)

where 0.2 % for Ps corresponds to 500 year return period and 1% for Pd corresponds to 100 year return period.

Then, ETC for an ordinary spatial structure can be expressed by equation (2).

$$Ct = 1{,}000{,}000 + n \times \left(\frac{1}{500} \times 1{,}000{,}000 + \frac{1}{100} \times 100{,}000 \right) \tag{2}$$

On the other hand, in case of TSS, we assume the following values;

Ci: 900,000 euros
Ps: 1 % (corresponding to 100 year return period)
Pd: 5% (corresponding to 20 year return period)
Cr: 90,000 euros (=1/10 of initial construction cost)

where values of Ps and Pd are reduced to 1/5 of those for an ordinary spatial structure, corresponding to shorter design working year, and, in addition, initial construction cost is assumed to reduce by 10% according to the reduction of design loads. Then, ETC for this structure is expressed by equation (3).

$$Ct = 900{,}000 + n \times \left(\frac{1}{100} \times 900{,}000 + \frac{1}{20} \times 90{,}000 \right) \tag{3}$$

In Fig. 1, ETC for an ordinary spatial structure and a TSS are compared. It is clear from the figure that ETC for TSS is lower than for ordinary spatial structure in the range of shorter working years. In other words, reduction of design loads has economic advantage and leads to better cost performance in the range of shorter working years.

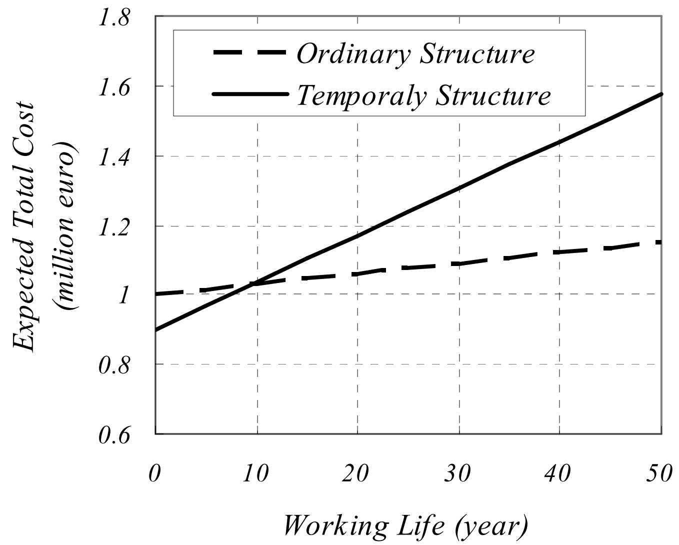

Figure 1 Comparison of ETC between temporary spatial structure and ordinary spatial structure

3.2 Risk to priceless possessions and human lives

Risk to priceless possessions and human lives will be discussed here. For convenience, human life represents the priceless possession and human life in this section.

Expected number of deaths is estimated by equation (4) after Mori [1].

$$De = Ps \cdot Np \cdot Pd \cdot n \quad (4)$$

where De : expected number of deaths

Ps : occurrence probability of safety limit load

Np : expected number of persons staying in a structure

Pd : probability of persons led to death

Assume following values in order to estimate the expected number of deaths;

Np : 100

Pd : 1%

Expected number of deaths for ordinary spatial structure is expressed by equation (5),

$$De = \frac{1}{500} \cdot 100 \cdot \frac{1}{100} \cdot n \tag{5}$$

and expected number of deaths for TSS is expressed by equation (6).

$$De = \frac{1}{100} \cdot 100 \cdot \frac{1}{100} \cdot n \tag{6}$$

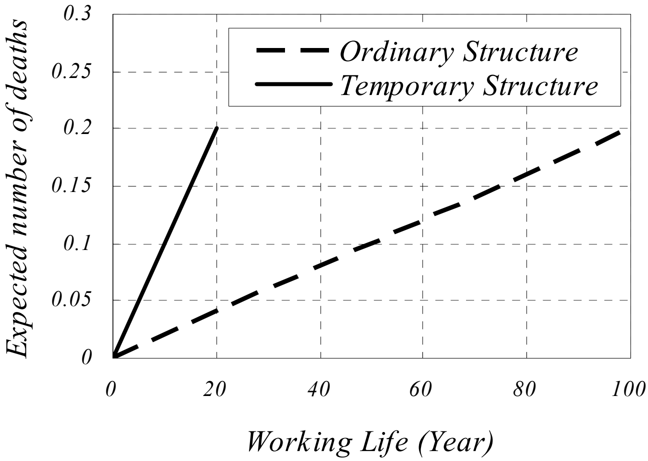

Figure 2 Comparison of expected number of deaths between for TSS and for ordinary spatial structure

Expected number of deaths throughout the design working year is 0.1 for both ordinary spatial structure and TSS. But, looking at the expected number of deaths per each working year, there can be observed a big difference; 0.1% for ordinary structure and 0.5% for TSS. This means that risk to human lives in TSS is far bigger than that in ordinary spatial structures. In order to reduce the risk to human lives in TSS, occurrence probability of safety limit load for TSS has to be reduced to the same level as for ordinary structure.

Equation (7) is a revised ETC for TSS. In this equation, according to the idea stated above, it is assumed that safety limit load for TSS is equal to that for ordinary spatial structure, and the increase of safety limit load raises the initial construction cost of TSS by 50,000 euros (N.B. In some cases, the increase of safety limit load may raise the initial construction cost of TSS up to the same amount as that of ordinary spatial structure.).

$$Ct = 950{,}000 + n \times \left(\frac{1}{500} \times 950{,}000 + \frac{1}{20} \times 95{,}000 \right) \quad (7)$$

Equation (7) can be called ETC for low-life-risk TSS. Figure 3 is a comparison of equation (2) and (7), where it is observed that the low life risk TSS has still economic advantage.

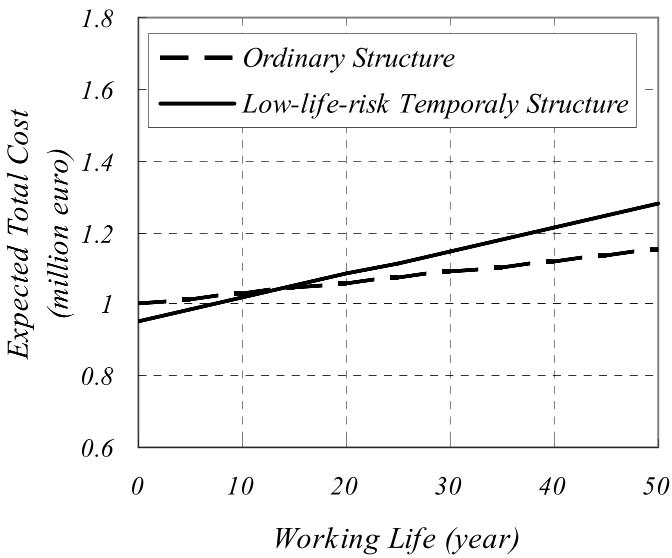

Figure 3 Comparison of expected total cost between low life risk TSS and ordinary spatial structure

4. Reduction of initial construction cost and safety control system

As shown in the preceding section, reduction of initial construction cost increases economic advantage of low-life-risk TSS. One of the methods to reduce initial construction cost is to provide TSS with a special system such as emergency countermeasure. The emergency countermeasure systems can be utilized to prevent possible damage caused by category 1 loads. Hereafter the emergency countermeasure system will be called as “safety control system” and characteristic properties to be provided by those systems will be discussed.

Safety control systems must work satisfactorily at every time they are needed, and so they have to be designed well in detail correspondingly. In order to keep the acting load less than a target level, the system should have the following functions:

(1) Data collection function; the system has to collect information necessary to predict the contact time and intensity of possible object load.

(2) Prediction function; the system has to predict contact time and intensity of possible object load. For this purpose, it is necessary to decide the following control levels beforehand;

a) Target levels of object physical quantities

b) Two threshold levels for each target level

Threshold A; This is a level near but lower than the damage limit or safety limit. This level is used when intensity of a hazardous phenomenon is getting stronger.

Threshold B; This is a level lower than threshold A, and is used when intensity of a hazardous phenomenon is getting weaker.

(3) Command function: When an object physical quantity is predicted to approach threshold A, this system must alarm to take an emergency countermeasure. On the other hand, when the loading condition goes down lower the threshold B, this system must make decision to take the emergency countermeasure off.

In figure 4, y-coordinate denotes loading action and structural resistance, and x-coordinate denotes time. Fig. 4 shows the change of loading action and resistance of a TSS with safety control system, when a hazardous phenomenon is approaching to and leaving from the TSS. Dotted line shows variation of loading action and solid line shows resistance. *La* and *Lb* show levels of threshold A and B, respectively. $R1$ is structural resistance of prototype TSS. $R2$ is structural resistance of TSS reinforced by emergency countermeasure.

When $t = t1$, loading action reaches *La*. At this time, safety control system directs to set emergency countermeasure. The setting work should be completed by the time when loading action reaches the level $R1$. The work has completed by $t = t2$ and the structural resistance of TSS is raised from $R1$ to $R2$. Thus, in the period later than $t2$, TSS can resist loading actions without any damage. $T1$ $(= t3 - t1)$ is a time interval allowed for setting temporary countermeasure. If loading action exceeds the level $R1$ during the period $T1$, some damage may occur to TSS.

At $t = t4$, loading action decrease to *Lb*, and safety control system directs to remove the temporary countermeasure away. The removal work finished at time $t5$, and TSS returns to the normal state. It will be noted that if the loading action would turn to upward direction and might reach the level *La* in a shot period as shown in figure 4 (thin dotted line), it might cause damage to TSS. Therefore, when loading action is predicted to go up to level *La* in a shorter interval *T2*, the direction of removal should not be issued.

In conclusion, the differences between *R1* and *La* and between *La* and *Lb* have to be decided appropriately taking the discussion stated above into consideration.

This safety control system can be applied not only to damage limit load, but also to safety limit load.

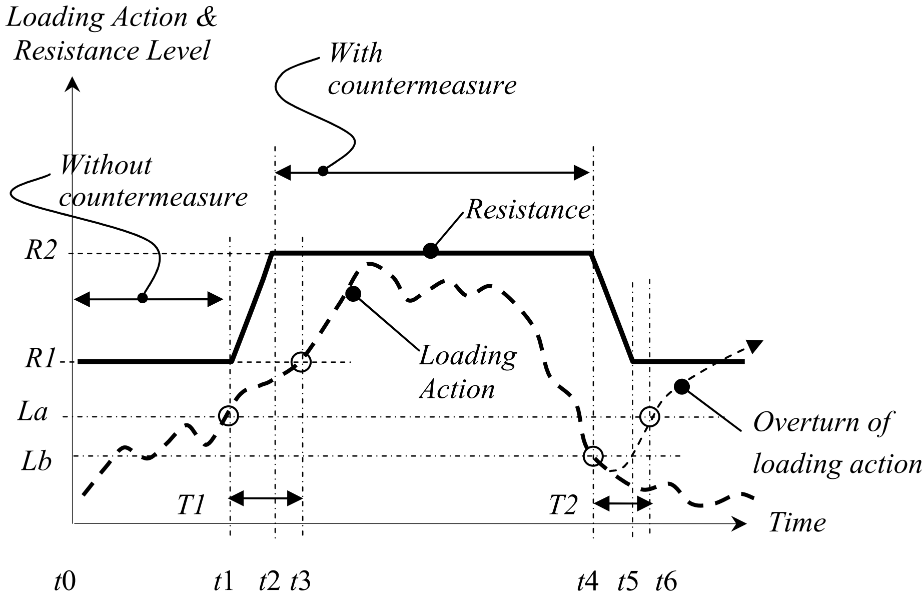

Figure 4 Action and resistance level of TSS with safety control system

5. Concluding remarks

Reductions of structural design load for TSS are discussed. It is concluded that reducing damage limit loads for TSS is reasonable as far as TSS is used for a shorter period. Risk to priceless possessions and human lives in TSS are far bigger than that in ordinary spatial structures. Therefore, if we want to reduce risk to human lives, safety limit loads assumed in the structural design of TSS are not recommended to be reduced.

Introduction of safety control system is effective to reduce structural design loads for TSS. Safety control system has to be designed to have functions of data collection, prediction, and command.

References

[1] ISO 2394, General Principles and Reliability for Structures, 1998

[2] Yasuhiro Mori Design loads, extension of term and renewal of temporary Buildings, written in Japanese, Proposal of guideline on reuse of building materials, Annual meeting of AIJ, 2008, 69-75