RELATION BETWEEN DESIGN LOAD LEVEL AND LIFETIME OF INDIVIDUAL BUILDING AND ITS ELEMENTS

Yukio Tamura*, Di Wu and Qingshan Yang
Beijing's Key Laboratory of Structural Wind Engineering and Urban Wind Environment, School of Civil Engineering, Beijing Jiaotong University, Beijing, China. *Email: yukio@arch.t-kougei.ac.jp

ABSTRACT

The common wisdom is to design cladding and components using a lower level wind load than the main structural frames, i.e. a shorter recurrence period wind load is used for cladding design than for frame design. This paper first discusses the design wind load levels for structural frames and for cladding and components. Next, the design wind loads of scaffolds for building construction, those of buildings in the construction stage, and those of so-called "temporary" structures such as site offices are discussed. In Japan, the design wind load for scaffolds is defined as 1-year-recurrence wind load, because its average setting period at one construction site is around 6 months, but this paper clearly proves the inappropriateness of this design wind load estimation concept. Then, it is shown that there is no relation between the design wind load level and its lifetime at an individual site. Finally, even for the design wind load for main structural frames, it is clearly demonstrated that the design load level may not be able to be determined based on the lifetime of an individual building. Therefore, although the LCC concept is applied in design load estimation, it is strongly recommended that the optimal design load level should be decided considering total LCC for the city or nation as a whole, and treat design as involving a group of buildings, rather than attempting to optimize the LCC of individual buildings. Clearly, the cost associated with social or national security must be included.

KEYWORDS

Design load level, building life time, cladding and components, temporary structures, individual use, LCC.

INTRODUCTION

There are several problems in the current codes and standards that need to be rectified if we are to produce wind-resistant buildings and structures. One of them is the recurrence period of the design wind load for structural frames and for cladding/components, namely the design wind load levels for structural frames and for cladding/components. The tendency is to design cladding/components using a lower wind speed than the main structural frames, i.e. a shorter recurrence wind load is used for cladding design than for frame design in some countries. For example, according to the Building Standard Law of Japan (BSLJ), allowable-stress design criteria are combined with 50-year-recurrence wind loads for structural frame design, and the same recurrence wind loads are used for cladding/components design. However, 500-year-recurrence wind loads are applied for the ultimate state structural frame design, while cladding/component design is not obligated to reach this design level. Accordingly, structural designers tend to ignore this level in cladding/component design. Some consider only 100 or 200-year-recurrence loads for cladding/components, leaving the 500-year-recurrence load for structural frames. Thus, it is implicitly understood that the design load level of cladding/components can be lower than that of structural frames. However, the validity of this understanding should be re-examined carefully.
A similar problem is seen with the design wind loads of scaffolds for building construction, and for those of so-called "temporary" structures such as construction site offices. For example, in Japan, the design wind load for scaffolds is defined as the 1-year-recurrence wind load, because the average setting period at a construction site is around 6 months (SCEAJ-TRSSW, 1999). However, this design wind load estimation concept is completely inappropriate as discussed later.
In this paper, a very primitive problem, namely the relation between the design load level and the lifetime of individual buildings or their parts is discussed.

LOAD LEVELS FOR MAIN FRAMES AND CLADDING/COMPONENTS OF BUILDINGS

Design Wind Load Estimation

There are some problems with the wind loads used in building design as mentioned in INTRODUCTION such as the different wind load levels for main frames and cladding/components. Even for just frame design, there are many problems. One of them is the Gust Loading Factor (GLF, Davenport 1967) or the Gust Response Factor

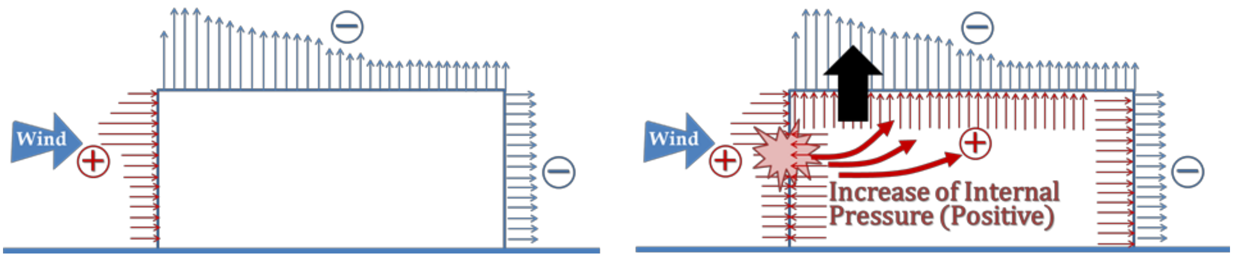
(GRF) used in the majority of building codes and standards in the world. Basically, the same GLF or GRF, which is based on the dynamic behavior of the building, is used for serviceability state design and also for ultimate state design. It is necessary to confirm conformance to "elastic GLF" or "elastic GRF" in the ultimate design stage, in which the building behaves in a plastic manner. Incidentally, in Japan, the ultimate design criteria for main structural frames allow member stresses to be within 1.1 times the allowable stress, i.e. only 10% larger than the elastic limit, so the building can behave in an "almost elastic manner". Thus, fully plastic behavior is not permitted and is not checked in design. Further studies are needed in this regard.

Furthermore, in general, the structural design of main frames uses the aerodynamic coefficient of the pristine building without cladding damage, so that the cladding and components are implicitly assumed to keep their original integrity. Therefore, theoretically, there is no reason to accept a lower level of wind load for cladding/components, except for cases considering the possibility of change in the aerodynamic coefficient or reaching a consensus with building owners and occupants or guaranteeing preventive measures of damage coherence or chain of damage. A minor failure of cladding/components can trigger destructive damage to the entire building.

Coherent Phenomena and Chain of Wind-Induced Damage

Structural designers are interested in main frame design, but not so much in cladding design. However, wind-induced damage is generally triggered by localized damage to cladding/components. This damage can propagate to much larger scales and even damage the main frames.

In general, positive pressures act on the windward wall, but negative pressures act on the other surfaces such as side walls, leeward wall, and roof surface as shown in Figure 1(a). In general, the internal pressure coefficient is negative. The wind force coefficient C_f acting on the roof structure is the difference of the external pressure coefficient C_{pe} and internal pressure coefficient C_{pi}, say $C_f = C_{pe} - C_{pi}$. Once a window pane on the windward wall is damaged, the air enters the building and the internal pressure coefficient C_{pi} becomes a high positive value. Therefore, the uplift (negative) wind force coefficient C_f suddenly becomes large through combination with the inherent negative external pressure coefficient C_{pe}. As shown in Figure 1(b). The same damage progression can happen with just minor damage to the eaves.



(a) Wind pressure distribution (b) Sudden increase in roof force

Figure 1 Wind pressure distribution and effects of sudden partial failure of the windward wall

This "coherent phenomenon" in damage progression is a special feature of wind-induced building damage. The separated parts of cladding and components can easily become wind-borne debris, and strike downstream buildings. Debris impacts also initiate cladding/components damage to downstream buildings. This "chain of damage" is another special feature of wind-induced damage to buildings in urban areas.

Property Losses due to Damage to Cladding/Components

If the window panes and claddings of a tall building fail, property inside the building would be seriously damaged and lose its value. This property loss can be very significant, especially if only the main structural frames remain. The miserable situation of a building with damaged window panes is often reported after extreme wind attacks in urban areas, e.g. Brewick *et al*., 2009 (Figure 2).

Super typhoon Haiyan attacked the Philippines on November 8, 2013, and caused serious disaster to this country and other surrounding countries. The recorded maximum 3s gust was 57m/s at Roxas City, Capiz, and the lowest pressure was 910hPa at Guiuan, Samar (PAGASA). The dead and missing numbered 7,986 (NDRRMC, January 14, 2014).

(a) Damage to window panes (b) Inside situation

Figure 2 Damage due to Hurricane Ike, 2008 (Brewick *et al*., 2009) (Courtesy of A. Kareem)

(a) Damage to roof cladding materials of EGS Contact Center

(b) Serious property damage inside and failure of business continuity planning (BCP)

Figure 3 Damage to steel structure due to Typhoon Haiyan (Palo, Leyte, the Philippines, 2013)

Figure 3(a) shows a steel frame structure whose main frames suffered almost no damage but whose metal roof sheets were widely damaged. Only the claddings failed significantly but there was serious property damage inside as shown in Figure 3(b). BCP (business continuity planning) was not successful and the business stopped for a long period. The cladding damage dealt a deathblow to the building owner. If one of the purposes of a building is to ensure business viability, the cladding cannot be destroyed. Even if the main frame survives without damage, it has no value. Thus, the importance of cladding/component design should be recognized, and it is essential to understand that "Wind Resistant Design" is equal to "Cladding/Components Design".

(a) Partial damage to metal roof sheets (b) Induced collapse of entrance sashes and doors

Figure 4 Partial damage to metal roof sheets induced collapse of entrance sashes/doors, and killed one person (Nobeoka tornado, 2006)

Figure 4(a) shows partial damage to the metal roof sheets of a super-market due to a tornado in Nobeoka, Japan. The opening created in the roof suddenly decreased the internal pressure and became negative because of the negative roof pressures, as can be understood from Figure 1(a). The wind loading across the windward wall increased significantly, and the entrance sashes and doors inwardly collapsed as shown in Figure 4(b). A person standing near the entrance doors was killed under the falling sashes and doors.

Cladding/component damage can propagate throughout the entire building, and can cause serious property losses to the building owners and society. Furthermore, even the partial failure of cladding/components can cause human loss.

These facts suggest that there is generally no reason to allow a lower design wind speed for cladding/components than main frames, unless property or human life are protected effectively and the damage chain is terminated. Thus, in general, the design wind load level for cladding/components should be the same as that for the main frames.

DESIGN LOADS FOR TEMPORARY-USE BUILDINGS AND STRUCTURES

Building Codes for Temporary Buildings

Design loads for temporary use buildings and structures including construction work offices are specified in the Building Standard Law of Japan. Their design loads can be lower than those of general buildings. Building codes specify the minimum requirement to keep social and national security. BSLJ specifies temporary buildings in Article 85. Temporary buildings include emergency structures after devastating disasters, emergency buildings for the public good after disasters, temporary buildings for construction works, and temporary stores/theaters/exhibition halls. AIJ-DRBLL (2013) recommends reduction of the design loads for the allowable stress design level excitations (almost 50y-recurrence level), if the occupants' safety is guaranteed for the ultimate limit state level excitations (almost 500y-recurrence level). ASCE 7-10 does not specify requirements for temporary structures. Accordingly, engineers may consult another standard, called ASCE 37, which addresses design loads on permanent structures in the construction stage, similar to temporary structures. For temporary structures with design life less than 6 weeks, a reduction factor of 0.75 is recommended to be applied to the design wind speeds. The Australian/New Zealand Standard (AS/NZS 1170.2:2011) defines structures with design life greater than 5 years as "permanent" and structures with design life less than or equal to 5 years as "temporary". The design wind speeds of temporary structures with varying design lifetimes are lower than is true for permanent structures. As shown in Figure 4, it might be difficult to guarantee the safety of human lives, but basically they simply believe that they can reduce the design load for temporary buildings.

Design Load for Scaffoldings

As mentioned in INTRODUCTION, the design wind load for scaffoldings is defined as the 1-year-recurrence wind load in Japan, because of its short average setting period at one construction site, 6 months for bare scaffolding and 4.5 months if sheets are used (SCEAJ-TRSSW, 1999). The British standard (BS EN 12812:2008) allows the wind pressure to be modified to take account of the period of use of the scaffolding; it is the recommendation of this standard that the minimum value of probability on a scaffolding structure be based on a two year return period. The Chinese standard (JGJ130-2011) recommends 10-year-recurrence wind loads for scaffolding design. However, this principle is not necessarily appropriate for design load estimation as mentioned in the previous section.

(a) Damage to scaffolding and induced car accidents (Hokkoku Shimbun, 2007)

(b) Damage to scaffolding and induced damage to neighboring buildings (Ohdo, 2007)

Figure 5 Damage to scaffolding

Figures 5(a) and (b) show damage to scaffolds in Japan and induced car accidents and damage to a neighboring building. In some cases, people working at the construction site or walking outside can be killed or injured. These facts suggest that the damage to scaffolds can cause secondary failure of/damage to others. As the structural system of scaffolding is not stand-alone, once it is damaged, the effects imposed on others are more significant than is true with general buildings.

Figure 6 Damage to construction work offices due to a tornado in Saroma-cho, Hokkaido, Japan, on November 6, 2006 (Tamura *et al*., 2007)

Figure 7 Simple foundation system of construction work offices shown in Figure 6 (Tamura *et al*., 2007)

Design Load for Construction Work Offices

Figures 6 and 7 show damage to construction work office buildings due to a tornado in Saroma, Hokkaido, 2006. Nine people died due to this damage. The foundation part is seen in Figure 7. Simple embedded short vertical posts supported wooden foundation girders and the superstructure was attached to them with iron clamps. Such buildings have clearly weaker ground anchorage than general buildings. As mentioned in the previous section, temporary buildings and structures can be constructed with lower design loads.

However, we cannot find any reason to accept lower design loads than general buildings. This kind of building is used in much the same way as a general building. Workers at a construction site have meetings, make drawings, conduct analyses, perform administrative works, meals, sleep, and so on in this type of building. There is no difference from other general buildings including their headquarter office building. Once a person takes a job in the construction company as a construction engineer, he should stay and work in this type of building until he retires, say for 40 years.

On the other hand, a person assigned as a designer of the same company can stay in a high quality building such as the headquarter office for the same 40 years, and do almost the same things. The site staff does not quit his job after finishing his 1 or 2-year work term at a certain construction site. He continues to work in construction work offices at different construction sites. Thus, the construction work office is a kind of permanent building for him. If the quality of the construction work office is lower than that of general buildings in term of safety level, he would face more risk than the office staff, but this should not be accepted.

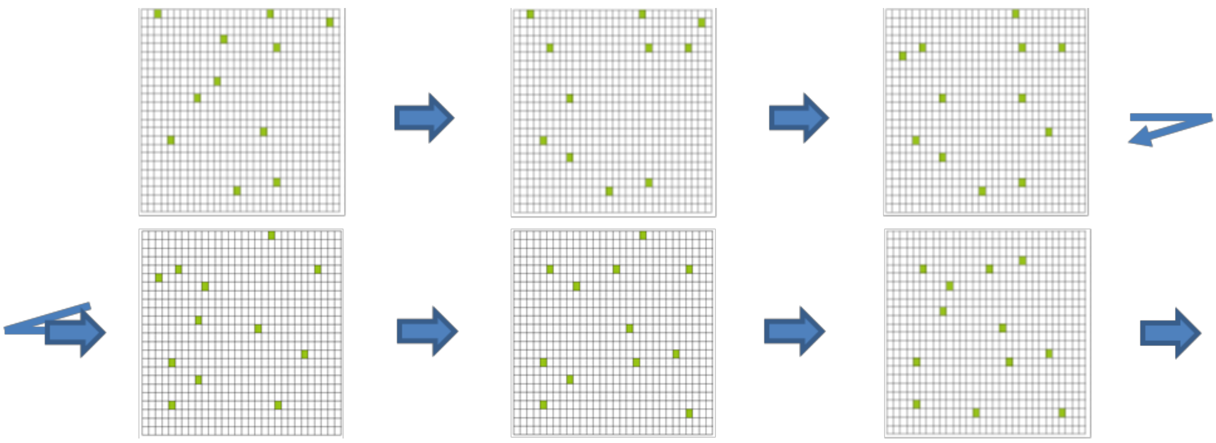


Figure 8 Schematic diagram of movement of scaffolding or construction work offices in a city model (6 month snapshots)

LENGTH OF LIFETIME AND INDIVIDUAL USE

Can Shorter Lifetime of Temporary Building for Individual Use be Reason of Lower Design Load?

Let's discuss the lifetimes of temporary buildings such as construction work offices or scaffoldings. Figure 8 shows a schematic diagram of a very simple city model, in which there are 30 × 24 = 720 buildings including construction sites. Each rectangular block represents a building, and green blocks indicate construction sites. The figure gives six snapshots of the city taken at 6 month intervals. The locations of the construction sites indicated by green blocks are basically different from snapshot to snapshot, which suggests the construction sites are moving but the number of construction sites remains basically constant. This mirrors real life.

If a strong earthquake or a strong typhoon attacks this city, all buildings, including general buildings (white blocks) and scaffolding or construction work offices (green blocks) would experience the same level of seismic load or wind load. There is no difference between the permanent and temporary blocks in terms of the existing period and the external environment.

Although a specific scaffold remains at an individual site for only a short period, i.e. average of 6 months, it moves to other places such that scaffolding is almost always present in the city or area. Although a specific scaffold is not be used for a long period, generic scaffolds always exist. The same is true for construction work offices.

If you look at a specific construction site, e.g. "construction site *i*", it disappears after a certain period, and so it seems to have a short fixed lifetime. However, if you look at construction sites in general, one or more always exist somewhere in the city the same as general buildings. Even for general buildings, a specific building has a certain lifetime, but similar structures are "always present". Staff assigned to work at construction sites are "always working" at a one or another construction work office, although the site often moves.

This suggests that the length of individual use of buildings and structures, i.e. the average period of 6 months for scaffolds or a few years for construction work offices, has no meaning with determination of design loads. We should design scaffoldings or construction work offices as permanent structures, rather than as temporary structures as they now are. The staff assigned to construction work offices do not see them as temporary, only as permanent structures.

Easier to understand examples are as follows. Even if the average rental period of an individual rental car is one day or one and a half days, the car cannot be designed based on this length of use. The renters will change but the car itself always exists. The fact that the users are temporary short has no meaning in terms of design, only the long-term use is important for car design. Even if some parts or bolts of an airplane are periodically replaced at predetermined intervals, those parts and bolts cannot be designed weaker than the main body based on the replacement interval. They should have the same performance as the main body.

Replacement of Cladding/Components for Maintenance

It is said that claddings and components are replaced more frequently than main structural frames, so the existing return periods for them are shorter than that of main frames. However, as explained by rental car example and airplane example in the previous section, this replacement has no meaning. A specific cladding element may be replaced at short predetermined intervals, but identical cladding element will replace it, and the cladding itself exists as long as the building exists.

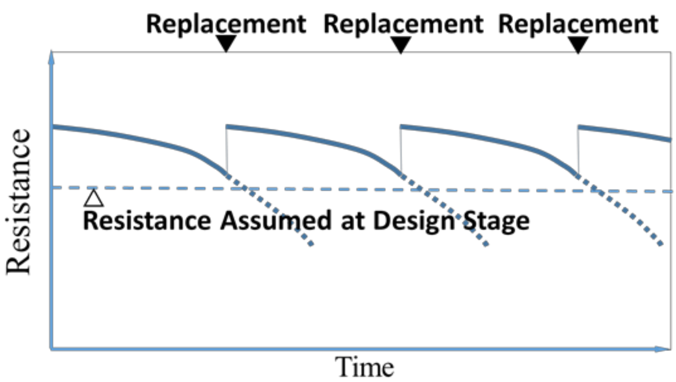


Figure 9 Replacement of elements for maintenance

The replacement is only maintenance to keep the element's quality or resistance up to the level assumed in the design stage as shown in Figure 9. The resistance level or design load level must not predicated on the replacement interval.
Thus, short replacement periods for specific cladding elements has no meaning in terms of wind load estimation. As cladding and component damage directly impacts the safety of the building and property, the structural designer should play an important role in guaranteeing their performance during strong winds.

Removal of Nets and Sheets for Strong Tropical Cyclones

By the way, the conventional wisdom is that the early warning systems of tropical cyclones allows nets or sheets covering scaffolding to be removed if strong wind is immanent, so a lower level of wind loads can be applied for scaffolding design, e.g. 1-year recurrence wind speed as specified in SCEAJ-TRSSW (1999). This is also obviously wrong.
Removal of nets and sheets changes only the physical parameters such as wind force coefficient C_f and projected area A_f. It cannot be a reason for accepting a reduction of design wind speed level V_d. The resultant wind force

$$F_d = (1/2)\rho V_d{}^2 C_f A_f \quad (1)$$

can be smaller because of the smaller wind force coefficient C_f or the smaller projected area A_f, but the recurrence year of the design wind speed V_d cannot be smaller. Thus, we can change and use appropriate C_f and A_f values depending upon the situation, but there is no relation between the design load level, i.e. design wind speed level V_d, and the removal of nets or sheets, and this point should be clearly noted.
Anyway, it should be clearly understood that there is no reason to use such a short design recurrence period, e.g. 1-year-recurrence wind load (SCEAJ-TRSSW, 1999), for scaffolds.

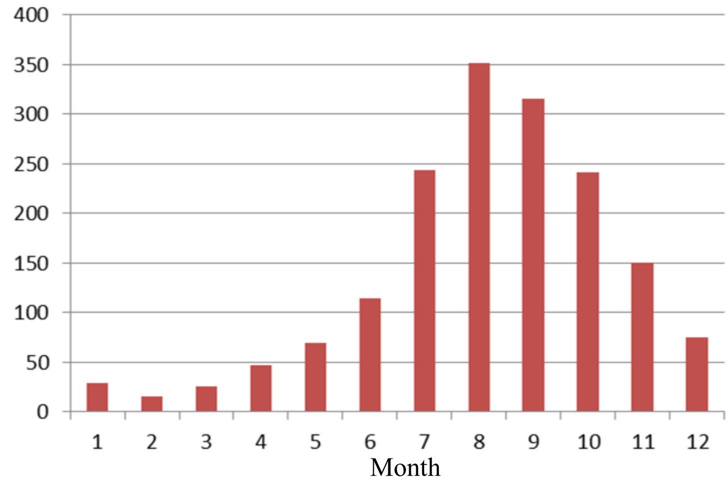


Figure 10 Monthly variation of number of typhoons (JMA, 1951-2014)

Seasonal Effects, Local Effects and others

Typhoons appear in the West Pacific region mainly in the warm season as seen in Figure 10, and there are significant seasonal effects. However, this is a wind climate problem. If a particular building is utilized only in the winter season, of course you need not consider the typhoon winds when you calculate design wind speed V_d. You can estimate design wind speed V_d based on wind speed records in winter seasons, or a seasonal factor can be used. This is similar to the geographic location effects. We can estimate design wind speed V_d based on the local wind climate.
It seems needless to say that these effects cannot be a reason for accepting a reduction in the recurrence period for the design wind speed estimation.

No Relation between Individual Lifetime and Social Importance or Damage Impacts

The discussions made above make it obvious that there is no relation between the design load level and the length or lifetime of individual use of cladding/components, scaffolds, and so-called temporary buildings.

It follows that the design wind load should be determined with clear recognition of the fact that so-called "temporary" buildings and structures never disappear and are always "present". Their design load level should be determined based on their acceptable collapse rate or damage rate in human society. Of course, it is not easy to determine an acceptable level of damage, because it depends on the importance of the target, social, economic and physical impacts of the damage, the economic situation of the society/nation, historical aspects, and so on.
So-called temporary buildings and structures tend to be treated as less important to society, but this is not necessarily true either. There is no essential relation between the social importance and the individual lifetime of a building part or an entire building. This should also be clearly noted.

RAISED PROBLEMS OF MINIMUM LIFE CYCLE COST APPROACH

Even for designing main structural frames to resist wind loads, the design load level may not be able to be determined based on the lifetime of an individual building. We use individual buildings, but each building is an important element forming the city or nation. The function of an individual building is of course important and should be considered in the design load estimation, but the function of the city and the nation is also very important. As such, the failure or damage rate of the assemblage of elements is important, not that of any one particular element.
As is well known, there is a concept for determining the optimal design load level based on a probabilistic consideration of the minimum Life Cycle Cost (LCC) of a building including initial construction cost and estimated repair cost over its estimated lifetime. However, although each building generally belongs to an individual as private property, it is one of the cells or elements composing a city or nation, and they are strongly related to each other through economic functions as well.
Business Continuity Planning (BCP) is an important issue not only for the private sector but also for a city or a nation, and securing BCP can be a key to the security of the city or nation. In particular, tall buildings have an aspect of social property, and damage to them has significant economic and social impacts on the community.
Under the above situation and considering the fact that the design load level cannot be decided based on the lifetime or length of individual use of a building or its parts, the concept of LCC should be re-examined. This raises the following question. Can "Life Cycle" be the length of the lifetime of the individual building? As it has been demonstrated, we should address the assemblage of buildings rather individual buildings. We have to re-examine whether we can decide the design load level based on the length of the individual building use.
When we make building codes or standards, we aim to specify the minimum requirements in order to keep essential and necessary security or safety level of our society which is undergirded by the vast number of buildings and structures. All of them must be designed as an assemblage and not in isolation. It is especially important that building codes and standards should be made based on this principle. It is strongly recommended that we re-examine the design load levels specified in some current codes, standards, and recommendations such as SCEAJ-TRSSW (1999), BSLJ Article 85 (2000), AIJ-DRBLL (2013), and so on.
Although the LCC concept has been adopted for design load estimation, the optimal design load level should be decided considering the overall LCC of the city or nation, rather than optimization of the LCC of an individual building. In that case, the costs imposed by securing social or national security should be addressed.

CONCLUDING REMARKS

The relation between the design load level and the length of individual use of a building or its parts was discussed. Most codes or standards tie the design load level to the lifetime of the individual building or building parts. However, it was clearly demonstrated that there is no rational reason for adopting this principle.
The aim of this paper was to merely clarify the problem of the relation between the design load level and the length of lifetime of buildings which has not necessarily been correctly understood.
More scientific discussion is needed to properly define so-called "temporary buildings". There might be more than two different types of temporary buildings. If we wish to decide the design load level of a building based on the length of its individual use, we should find a rational reason for it. Acceptable impact to society and acceptable probability of infrastructure failure should be directly discussed when determining design load levels. The acceptable criteria can be also depend upon the nation's economic situation. Anyway, many relevant problems remain to be solved.

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