STRUCTURAL CHARACTERISTICS OF EXISTING HIGH-RISE RC BUILDINGS IN JAPAN

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SUMMARY:
The paper presents studies of structural characteristics of high-rise RC buildings in Japan. The data on structural characteristics of 555 high-rise RC buildings designed from 1971 to 2009 was collected. The buildings were classified into three phases, focusing on the development of structural techniques on high-rise RC buildings, and the collected data was analyzed. The following remarks have been found. 1) The strength of concrete and steel bars for structures increased with the time. As a result, the number of stories, span length and typical floor area supported by a column increased. 2) The seismic isolation structures and seismic structures with energy dissipation devices largely increased in number after the 1995 Kobe earthquake. 3) Recent high-rise RC buildings tend to use smaller design base shear coefficient than those of early phase. 4) The maximum response story drift angle under very rare earthquake ground motions has gradually increased with the phase.

Keywords: Reinforced concrete, High-strength concrete, High-rise building, Earthquake response

1. INTRODUCTION

In Japan, with development of the high strength materials of both concrete and reinforcing steel bars, high-rise RC buildings have been very popular in recent years. The number of high-rise RC buildings had increased in the big cities, especially Tokyo and Osaka. There has been a demand to high-rise buildings using reinforced concrete system, in particular, for condominium and apartment houses, since RC buildings has the advantage in sound insulation, vibration insulation for wind, fire resistant performance and others as well as construction cost compared to that of steel buildings.

To evaluate structural characteristics of high-rise RC buildings in Japan, the data on structural characteristics of 555 high-rise RC buildings designed from 1971 to 2009, for approximately 39 years, was collected. These high-rise RC buildings were classified into three periods by means of the development of structural techniques on high-rise RC buildings. The collected data was analyzed, focusing on structural characteristics such as structural type, framed data, concrete, steel bar, natural period, base shear coefficients and seismic responses.

This paper presents studies of structural characteristics of existing high-rise RC buildings in Japan. The evaluation of structural data of existing high-rise RC buildings is important for discussion on seismic safety and development of high-rise RC buildings in Japan.

2. HISTORICAL TRENDS

2.1. Data on high-rise RC buildings

The structural design regulations on high-rise buildings were defined in 1963. High-rise buildings were defined as being over 45 meters high and special buildings over 31 meters. After the revision of the building standard law in 1981, high-rise buildings were defined as being over 60 meters high. At present, high-rise buildings have to be designed using time history analysis using earthquake ground motions. The method of time history analysis is defined by the building standard law in 2000.

To collect the data on high-rise RC buildings in Japan, the performance evaluation sheets are used. The performance evaluation sheets are described by structural designers after getting approval for the design by designated organizations which carry out performance evaluation of high-rise RC buildings. By analysis of the performance evaluation sheets on high-rise buildings designed from 1971 to 2009, the data on 555 high-rise RC buildings, for approximately 39 years, was collected.

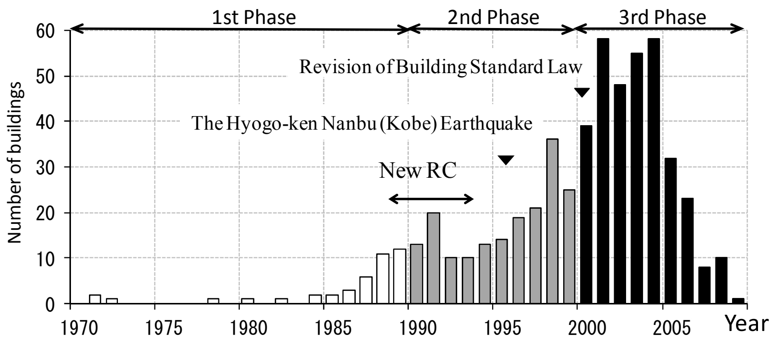
2.2. Structural design phases

The birth of high-rise RC building occurred in 1972. In the 1980's, under 10 buildings were constructed a year. After 1995, the number of high-rise RC buildings increased rapidly. From 2001 to 2004, over about 50 high-rise RC building were constructed a year.

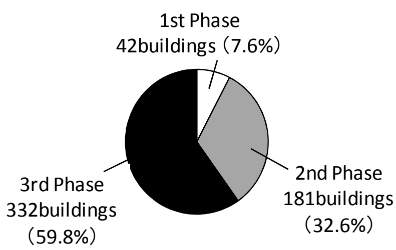
During the period of 1988 to 1993, the so-called national research project "New RC Project: Development of advanced Reinforced Concrete Buildings with High strength and High quality Materials" was carried out. The development of high-rise RC buildings in Japan was accelerated by New RC Project.

The 1995 Hyogo-ken Nanbu (Kobe) Earthquake caused the significant damage of reinforced buildings which were built before 1981 in Kobe. After this earthquake, seismic safety gained a growing interest in Japan. As a result, the seismic isolation structures and seismic structures with energy dissipation devices largely increased in number.

The structural design record for high-rise RC buildings using the total number of buildings is summarized in Figure 1. The approximately 39 years' amount of data on 555 high-rise RC buildings designed from 1971 to 2009 is divided into three phases by means of the progress of the structural techniques. The first phase (1972- 1989) is the establishment phase, the second phase (1990- 1999) is the development phase, and the third phase (2000- present) is the multiplicity phase.



(a) Transition on number of buildings



(b) Rate of three phases

Figure 1. Structural design phases for high-rise RC buildings

In the first phase, the construction of high-rise RC building begun and structural design method for future high rise RC buildings was established. In the second phase, the structural techniques on design and construction were developed by the New RC Project. The Hyogo-ken Nanbu (Kobe) Earthquake occurred in 1995. After 1995, many high-rise RC buildings had been constructed in Tokyo and Osaka. In the third phase, the number of high-rise RC buildings had increased rapidly. High-rise RC buildings have been very popular after 2000. In recent years, the high-rise RC building has reached about 60 stories with over 100MPa high strength concrete and SD685 high strength steel bars.

3. STRUCTURAL PLANNING

3.1. Structural Type

The structural type of high-rise RC buildings is summarized in Figure 2. To minimize serious damage of high-rise RC buildings subjected to strong earthquakes, damage control techniques such as energy dissipation device (hysteretic or viscous device) and base isolation system were introduced in the structural design of high-rise RC buildings. After the 1995 Hyogo-ken Nanbu (Kobe) Earthquake, the seismic isolation RC structures and seismic RC structures with energy dissipation devices largely increased in number.

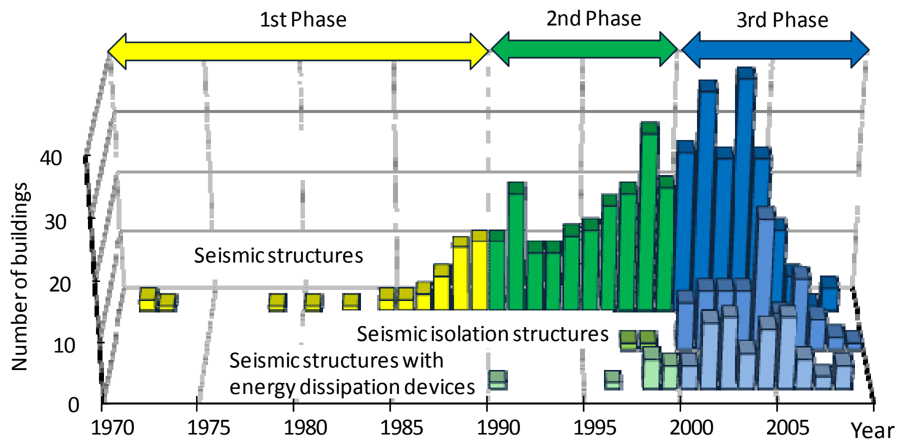
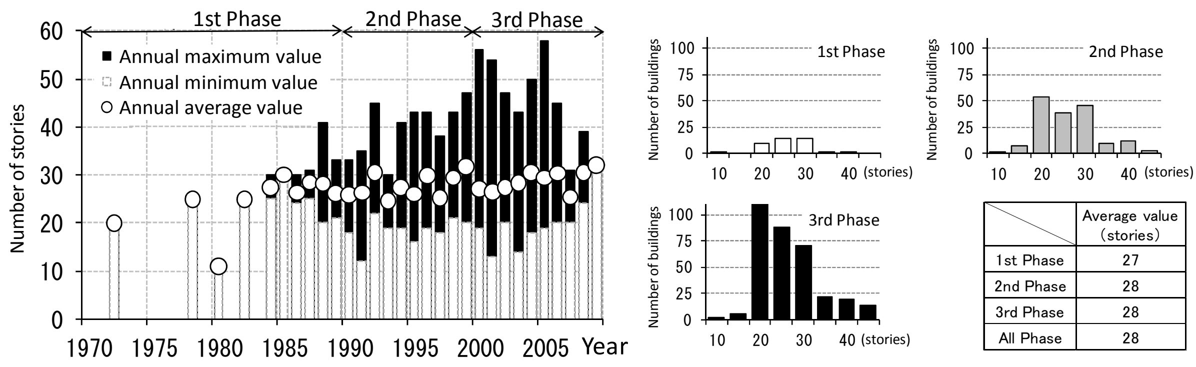


Figure 2. Transition on number of high-rise RC buildings with structural type

3.2. Framed data

This section shows basic framed data such as number of stories, area of standard floor, span length and typical floor area supported by a column.

Figure 3 shows the number of stories of high-rise RC buildings. High-rise building began 20-stories in 1972, reached over 40-stories in the second phase. In the third phase, around 60-stories building was designed. Over the past 39 years, the number of stories is approximately three times higher than the first building. The average number of stories is around 28-stories at each phase.



	Average value (stories)
1st Phase	27
2nd Phase	28
3rd Phase	28
All Phase	28

(a) Transition on number of stories

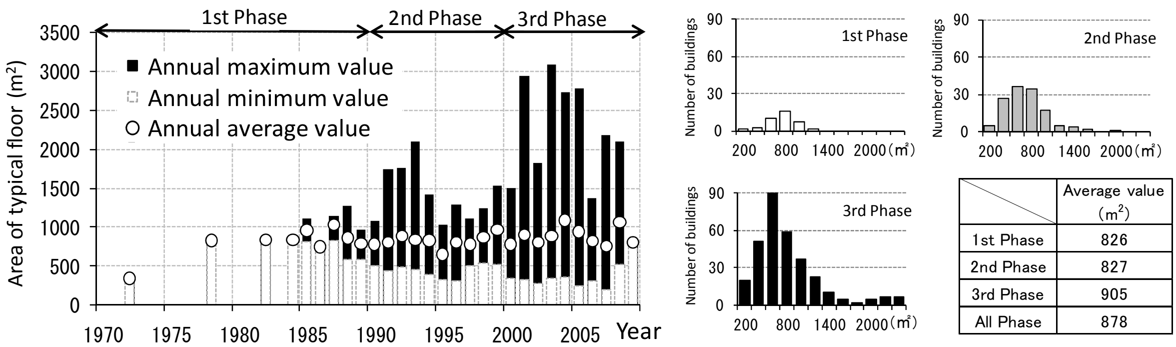
(b) Average of stories in the phase

Figure 3. Number of stories of high-rise RC buildings

Figure 4 shows the area of standard floor of high-rise RC buildings. The average area of standard floor was around 800 square meters in the first phase and the second phase. In the third phase, the average area of standard floor was around 900 square meters.

Figure 5 shows the span length of high-rise RC buildings. The first high-rise RC building in 1972 has a span length of 4.5 meters and 3.0 meters. In the first phase, the average span length was around 5.2 meters. The span length increased with the phase and the average span length was around 6.5 meters in the third phase.

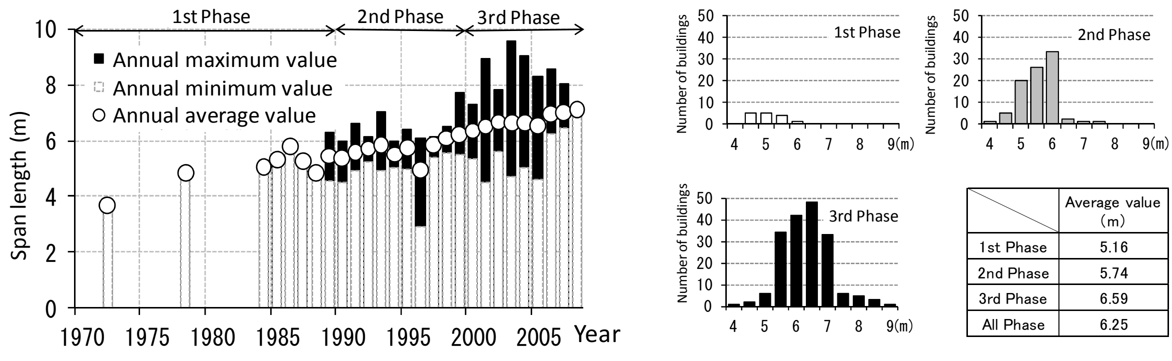
Figure 6 shows the typical floor area supported by a column of high-rise RC buildings. Although the typical floor area supported by a column was around 27 square meters in the first phase, it increased up to 44 square meters in the third phase. As the typical floor area supported by a column becomes larger, columns need higher strength concrete for case of the same column section area.



	Average value (m²)
1st Phase	826
2nd Phase	827
3rd Phase	905
All Phase	878

(a) Transition on area of standard floor (b) Average of area in the phase

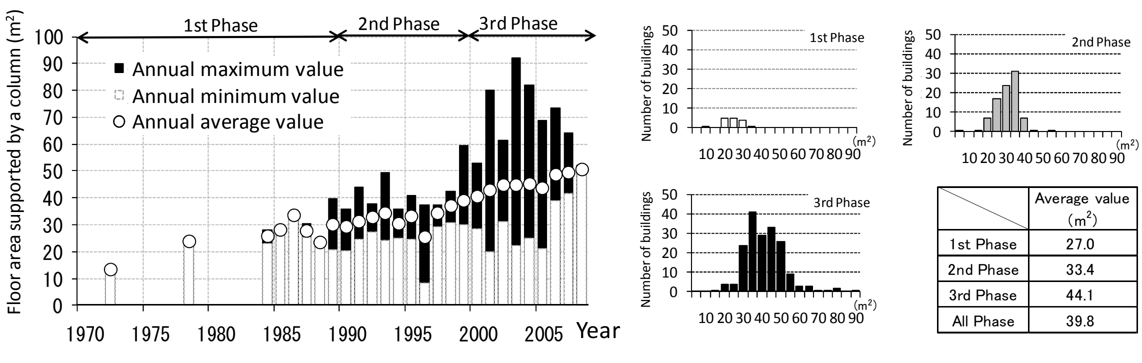
Figure 4. Area of standard floor of high-rise RC buildings



	Average value (m)
1st Phase	5.16
2nd Phase	5.74
3rd Phase	6.59
All Phase	6.25

(a) Transition on span length (b) Average of span length in the phase

Figure 5. Span length of high-rise RC buildings



	Average value (m²)
1st Phase	27.0
2nd Phase	33.4
3rd Phase	44.1
All Phase	39.8

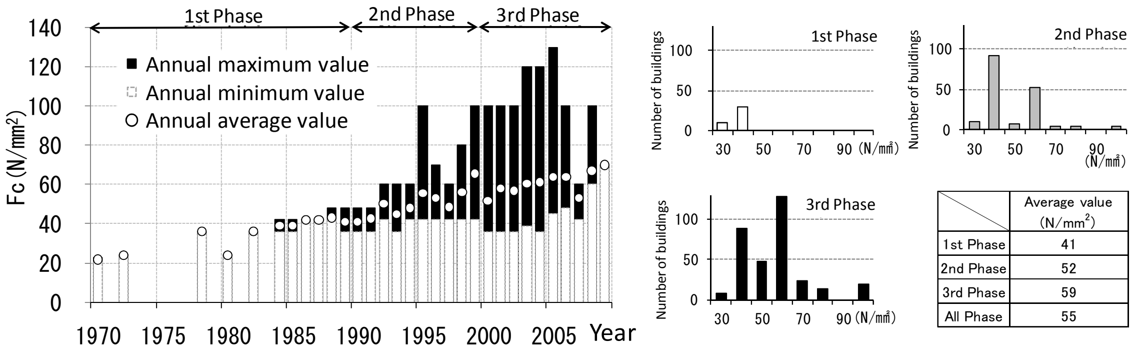
(a) Transition on floor area supported by a column (b) Average of area of stories in the phase

Figure 6. Typical floor area supported by a column of high-rise RC buildings

3.3. High strength concrete

Figure 7 shows the design compressive strength (Fc) of concrete which was used in high-rise RC buildings. The first high-rise RC building in 1972 used Fc30MPa concrete. The design concrete strength reached Fc42MPa. In the second phase, the design concrete strength reached Fc60MPa and Fc100MPa. Over Fc100MPa concrete was used in the third phase.

The development of high strength concrete was accelerated by the New-RC project (1988- 1992). When New RC Project had been initially proposed, the design compressive strength was greater than 30MPa. The concrete whose design compressive strength was greater than 60MPa was named the ultra-high strength concrete. In the third phase, high strength concrete with design compressive strength of 60MPa was usually used for frames of over 30-stories RC buildings. Ultra-high strength concrete with design compressive strength of over 100MPa was used for frames of over 50-stories RC buildings. At present, Ultra-high strength concrete with design compressive strength of about 180MPa has been used.



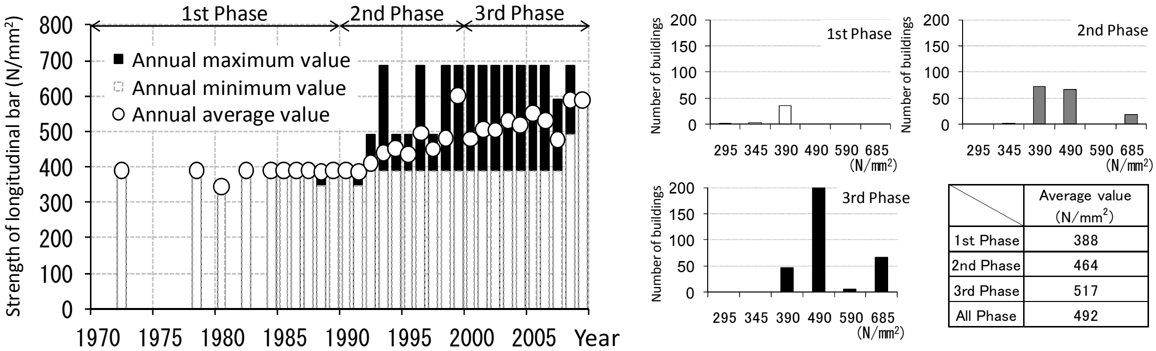
(a) Transition on design compressive strength (b) Average of strength in the phase

Figure 7. Design compressive strength of concrete for high-rise RC buildings

3.4. High strength steel bar

Figure 8 shows the tensile yield strength (fy) of longitudinal bar which was used in high-rise RC buildings. The first high-rise RC building in 1972 used 390MPa reinforcing steel bars. In the second phase, the strength of reinforcing steel bar reached 685MPa. In the third phase, 685MPa reinforcing steel bars were used usually for frames of over 45-stories RC buildings.

The development of high strength reinforcing steel bar was accelerated by the New-RC project as well as high strength concrete. When New RC Project had been initially proposed, the strength of reinforcing steel bar was greater than 390MPa.



(a) Transition on strength (b) Average of strength in the phase

Figure 8. Tensile yield strength of longitudinal bar for high-rise RC buildings

4. STRUCTURAL CHARACTERISTICS

In the evaluation of structural characteristics, the seismic structures of high-rise RC buildings were analyzed except for the seismic isolation RC structures and seismic RC structures with energy dissipation devices. The number of the seismic structures of high-rise RC buildings was about 370.

4.1. Seismic design of the seismic structures

The performance of high-rise RC buildings must be examined by earthquake response calculation solving the equation of motion. The performance requirement of a high-rise RC building under rare earthquake ground motions (level 1) is not to cause damage in structural members. The performance requirement of a high-rise RC building under very rare earthquake ground motions (level 2) is not to collapse. The design method is usually composed of the following two stages, the static design of using static seismic loads, and the dynamic design of using dynamic ground motions. After 2000, the technical standard for the structural calculation method of high-rise RC buildings was defined by ministry of construction notification.

The intensity of earthquake motions for the design of high-rise RC buildings had been defined using maximum acceleration of earthquake motions in the prime stage, whereas the maximum velocity has been used to express the intensity of earthquake motions. The intensity of maximum velocity for design has been decided depending on the seismic zone factor in Japan. The rare earthquake ground motions (level 1) have been set up from 200 mm/sec to 250 mm/sec. The very rare earthquake ground motions (level 2) have been set up from 400 mm/sec to 500 mm/sec. After 2000, the calculation of design earthquake ground motions was defined by ministry of construction notification. Artificial earthquake motions have to be used for design of high-rise RC buildings except for observed earthquake motions. The maximum velocity of observed earthquake ground motions is normalized to 250 mm/sec for level 1, and 500 mm/sec for level 2. Artificial ground motions compatible with a response acceleration spectrum specified by the notification at the open engineering bedrock must be generated. The generated earthquake motions at the engineering bedrock are amplified to take into consideration the effect of surface geology above the engineering bedrock.

A structure of a high-rise RC building is usually static analyzed under monotonically increasing lateral forces considering member stiffness changes at cracking, flexural yielding and shear deformation, because high resistance is provided against shear failure in design. By the static analysis, the relation between story shear and story shear drift is obtained for each story to make a multi-mass multi-spring model (the equivalent flexure-shear model and others). Mass is assumed to concentrate at each floor level. Story drift is divided into an elastic flexural component and a nonlinear shear component. The relation between story shear and shear spring deformation is idealized by a tri-linear relation. Degrading tri-linear hysteresis such as Takeda Model and others are used for the story shear spring. Damping is normally assumed to be proportional to instantaneous stiffness of the structure. Moreover, the dynamic analysis of the whole frames is conducted to evaluate the response status of structural members under the specified level2 earthquake ground motion that develop maximum response by the equivalent flexure-shear model.

For structural design of a high-rise RC building under rare earthquake ground motions (level 1), the stress at critical sections under member actions has to be less than allowable stresses of materials for short-term loading. The linear story shears are determined as the envelope of maximum story shears calculated for all ground motions. Static linearly elastic analysis of the structure as designed is carried out under the design story shears.

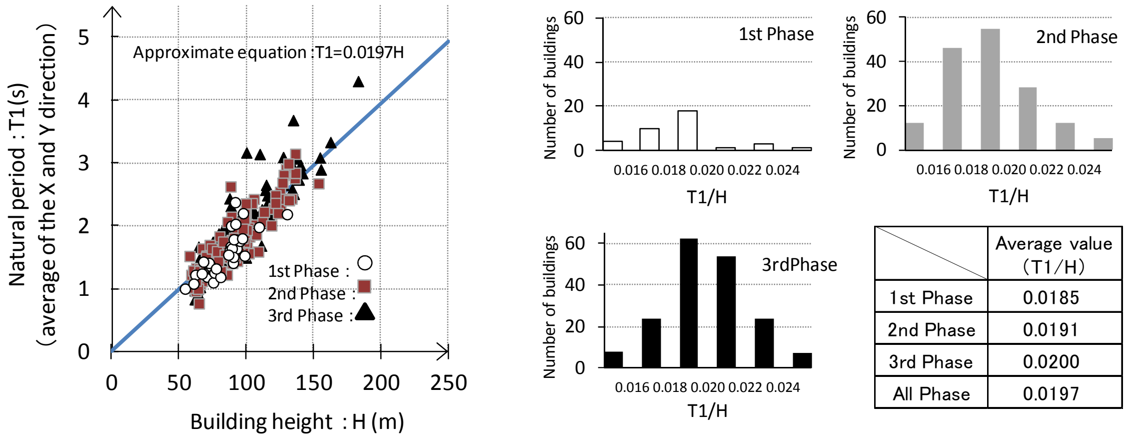
The story drift calculated for the mass-spring system must be less than 1/200 radian so that non-structural elements should not be damaged by level 1 earthquake ground motions.

The maximum story drift is generally required to be less than 1/100 radian so that the maximum story ductility factor of any shear spring is required to be less than 2.0 by level 2 earthquake motions.

4.2. Natural period

Figure 9 shows the relationship between natural period and building height of high-rise RC buildings, where the period is average of the X and Y direction and the building height means the eaves height. The natural period (T1 second) of the seismic structures has a linear relationship with building height (H meter). The linear approximate equation can be expressed as, T1=0.0197H.

In the first phase, the linear approximate equation can be expressed as, T1=0.0185H. In the third phase, the linear approximate equation can be expressed as, T1=0.0200H. The coefficient of the relationship between natural period and building height (T1/H) has gradually increased with the phase, because span length and thickness of floor slab of housing room increased.



	Average value (T1/H)
1st Phase	0.0185
2nd Phase	0.0191
3rd Phase	0.0200
All Phase	0.0197

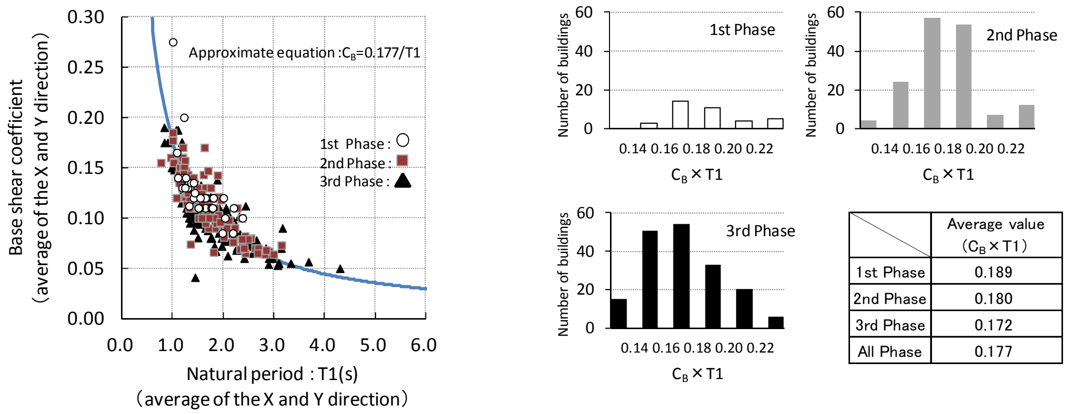
(a) Relationship between natural period and building height (b) Average of T1/H in the phase

Figure 9. Natural period and building height of high-rise seismic RC buildings

4.3. Base shear coefficients

Figure 10 shows the relationship between base shear coefficients and natural periods of high-rise RC buildings, where the base shear coefficient and the period are average of the X and Y direction.

Base shear coefficients (C_B) distributed around the approximate equation with C_B=0.177/T1. To compare with each phase, the approximate equations of the first phase and the third phase are C_B=0.189/T1 and C_B=0.172, respectively. Recent high-rise RC buildings tend to use smaller design base shear coefficient than those of early phase for case of the same natural period.



	Average value (C_B × T1)
1st Phase	0.189
2nd Phase	0.180
3rd Phase	0.172
All Phase	0.177

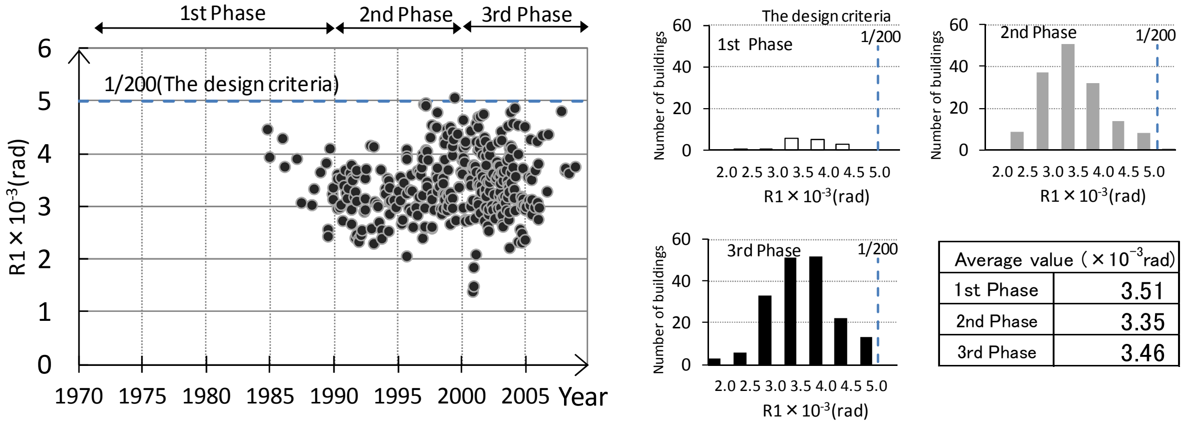
(a) Relationship between base shear coefficients and natural period (b) Average of C_B×T1 in the phase

Figure 10. Base shear coefficients and natural periods of high-rise seismic RC buildings

4.4. Seismic response

Figure 11 shows maximum response story drift angle of high-rise seismic RC buildings under level 1 rare earthquake ground motions.

Most data for R1 (Maximum response story drift angle under level 1 rare earthquake ground motions) is less than the design criteria of 1/200 radian. The average of R1 was around 1/300 radian (the second phase) – 1/285 radian (the first phase), because level 1 rare earthquake ground motions do not show significant changes.

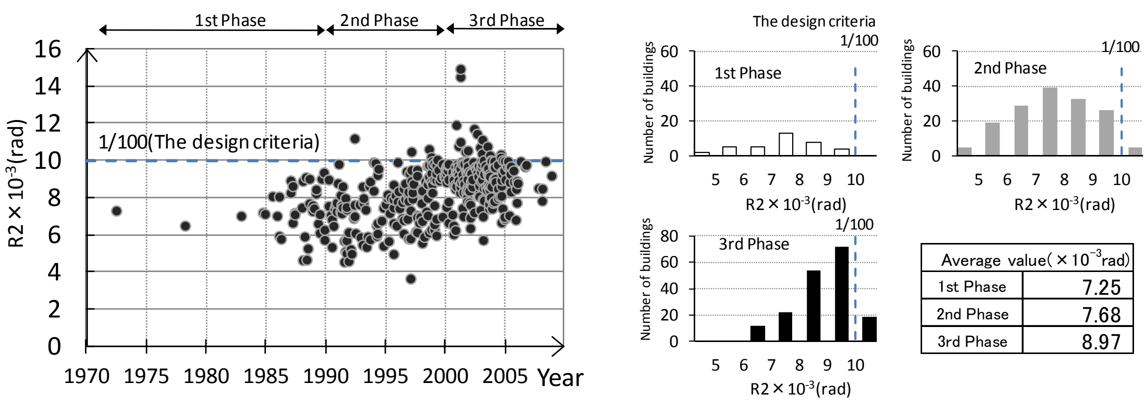


(a) Transition of R1 (b) Average of R1 in the phase

Figure 11. Maximum response story drift angle of high-rise seismic RC buildings under level 1 rare earthquake ground motions

Figure 12 shows maximum response story drift angle of high-rise seismic RC buildings under level 2 very rare earthquake ground motions.

Some seismic structures have over 1/100 radian for R2 (Maximum response story drift angle under level 2 very rare earthquakes) in the second phase and third phase, whereas there are a few buildings which R1 is over 1/200 radian. In the first phase, the average of R2 was around 1/140 radian. In the third phase, the average of R2 was around 1/110 radian. R2 has gradually increased with the phase, because the structural design conditions such as structural system and input earthquake ground motion level have been changed. The maximum story ductility factor under level 2 very rare earthquakes as well as maximum response story drift angle has gradually increased with the phase.



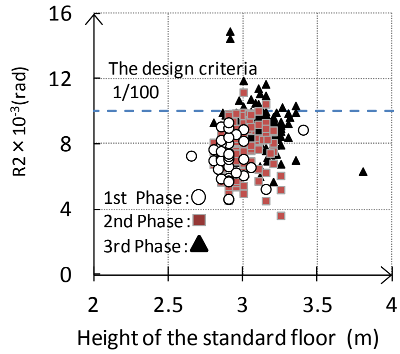
(a) Transition of R2 (b) Average of R2 in the phase

Figure 12. Maximum response story drift angle of high-rise seismic RC buildings under level 2 very rare earthquake ground motions

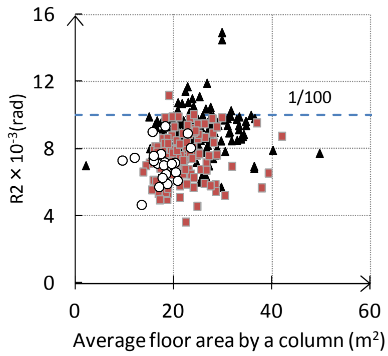
4.5. Seismic response story drift angle and framed data

Figure 13 shows the relationship between maximum response story drift angle (R2) of high-rise seismic RC buildings under level 2 very rare earthquake ground motions and framed data such as height of the standard floor, average floor area by a column, span length and aspect ratio. The average floor area by a column is calculated as the fraction of floor area by the number of columns. The aspect ratio is calculated as the ratio of building height to the building short side length.

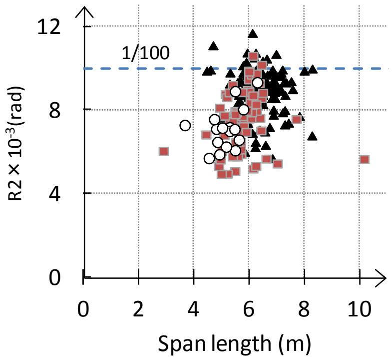
As well as framed data has gradually increased with the phase, R2 has gradually increased with the phase.



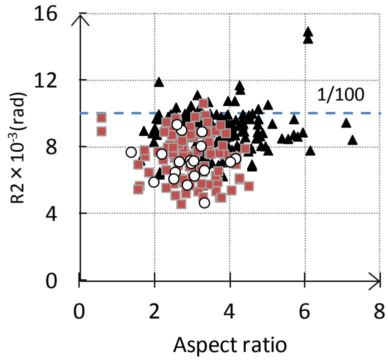
(a) R2 versus height of the standard floor



(b) R2 versus average floor area by a column



(c) R2 versus span length



(d) R2 versus aspect ratio

Figure 13. Relationship between R2 and framed data of high-rise seismic RC buildings

4.6. Seismic response story drift angle and base shear coefficients in the phase

Figure 14 shows the relationship between maximum response story drift angle (R2) and base shear coefficients (C_B) of high-rise seismic RC buildings.

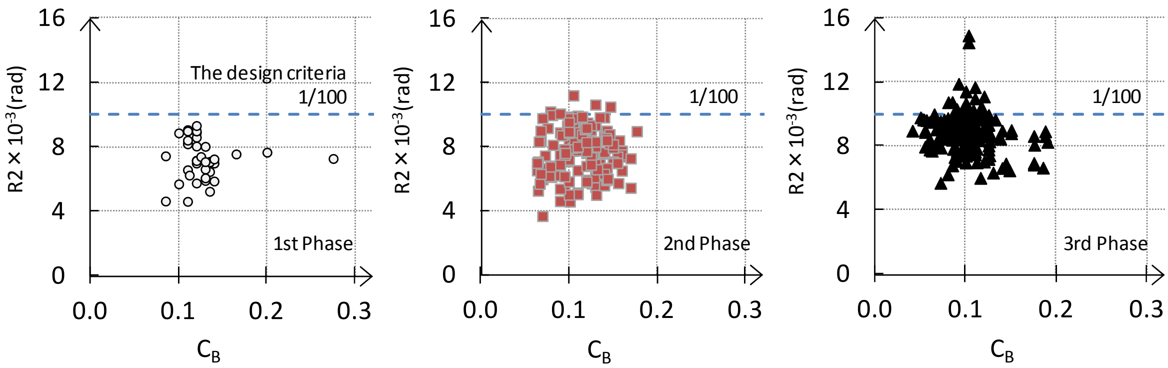


Figure 14. Relationship between R2 and C_B of high-rise seismic RC buildings

The base shear coefficients (C_B) of high-rise seismic RC buildings have gradually decreased with the phase, while R2 has gradually increased with the phase.

5. CONCLUSIONS

The following remarks have been found:
1) The strength of concrete and steel bars for structures increased with the phase. As a result, the building height, aspect ratio and column supporting floor area increased.
2) The seismic isolation structures and seismic structures with energy dissipation devices largely increased in number after the 1995 Hyogo-ken Nanbu (Kobe) Earthquake.
3) Recent high-rise RC buildings tend to use smaller design base shear coefficient than those of early phase for case of the same natural period.
4) The maximum response story drift angle due to level 2 very rare earthquake ground motions has gradually increased with the phase, partly because the structural design conditions such as structural system and input motion level have been changed.

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