STATISTICAL ANALYSIS OF CONCRETE STRENGTH IN EXISTING REINFORCED CONCRETE BUILDINGS IN JAPAN

Yasushi SHIMIZU[1], Masaya HIROSAWA[2] And Jiandong ZHOU[3]

SUMMARY

Estimation of concrete strength in existing concrete structures becomes necessary when inspecting the seismic resistance and retrofitting the existing structures. This study aims to provide a basic information necessary for estimating the concrete strength in existing reinforced concrete structures in Japan. More than *10788* cores were sampled from *1130* existing buildings and subjected to statistical analysis to estimate compressive strength of the existing structures. Effect of the design strength and the date of completion upon the compressive strength are also studied.

The major findings are as follows.

(1) Compressive strength showed changes by the floor in the same building even though the placing conditions of concrete was all the same.

(2) Average compressive strength increased and exhibited less chance to become low strength when the date of completion became younger.

(3) Coefficient of variation of the compressive strengths was tabulated with the design strengths and the date of completion.

(4) Significant number of existing buildings had very low concrete strength.

INTRODUCTION

Estimation of concrete strength in existing concrete structures becomes necessary when evaluating their seismic capacity and designing seismic strengthening. The qualities of the existing concrete structures are likely to degrade with time and normally difficult to estimate. It is therefore important to analyze statistical strength of core specimens taken from existing buildings rather than applying NDT or semi-NDT methods.

After the 1995 Hyogo-ken Nanbu earthquake, many seismic diagnosis have been executed and considerable concrete core strength data have been obtained associated with the quality inspection of existing concrete structures.

This paper deals with the statistical compressive strength using *10788* core samples from *1130* existing reinforced concrete buildings, and aims to contribute to the subsequent quality evaluation practice of existing concrete buildings. An average value of compressive strength of each building, its coefficient of variation (*CV*) and their relevance to design strength and the completed year of building are discussed.

[1] *Instructor, Technical High School, Tokyo Institute of Technology, Tokyo, Japan Email: shimizu@ths.titech.ac.jp*
[2] *Department of Architecture, Faculty of Engineering, Kogakuin University, Tokyo, Japan Email: dt10760@ccs.kogakuin.ac.jp*
[3] *Department of Architecture, Faculty of Engineering, Kogakuin University, Tokyo, Japan Email: dt10760@ccs.kogakuin.ac.jp*

OBJECTS OF THE RESEARCH

Research objects and testing methods

In this report, we will take compressive strength as a quality parameter of concretes in structures. The compressive strength was determined by a public testing laboratory-using cores of *10 cm* in diameter sampled from structures.

Testing method was based on *JIS A 1107* "Method of taking cores and beams from concrete structures and testing the compressive strength" and each end of a core was polished or capped with sulfur or gypsum.

Buildings inspected and core specimens

Total number of buildings selected to inspect concrete strength were *1130* including public schools and public office buildings and *10788* cores were sampled. The details of inspected buildings are shown in Table 1, and the details of cores are shown in Table 2.

Items recorded for each building were date of completion, location, usage, name of the owner, story, building area, design strength of concrete and type of concrete. Data types recorded for each cores were names of building, stories and structural elements of sampling, dimensions of cores, compressive strength and unit weight.

COMPRESSIVE STRENGTH OF CONCRETES IN EACH BUILDING

Distributions of compressive strength in buildings

Frequency distribution of each average compressive strength μ and the standard deviation σ of all buildings are shown in Figure 1 and Figure 2, respectively. Frequency distribution of coefficient of variation (*CV*) of compressive strength for all buildings is shown in Figure 3. Data employed in Figure 1, 2 and 3 is from *1102* building excluding *28* buildings where only one or two cores were sampled.

Completed years	Building use	Total floors	Total areas(m^2)
1926's 1984's	school, office	1 10	193 8535

Table 1: Details of investigated buildings

Table 2: Relationship of floor, member with the amounts of core

Floor	Numbers of cores	Members	Numbers of cores
5	141	Wall	10176
4	1048		
3	2640	Beam	201
2	3195		
1	3558	Others	411
Others	206		
Total	10788	Total	10788

In *36* buildings, average compressive strength was less than *13.5 MPa*, and of the *9* buildings, it was less than *10.0 MPa*. Standard deviation of compressive strength was more than *7.0 MPa* for *150* buildings, and of the *19* buildings, it was more than *10.0 MPa*. From the *CV* of the compressive strength shown in Figure 3, *78* buildings have their *CV* more than *0.35*. These imply that compressive strength of the buildings inspected has considerable variation and there are so many buildings of low strength concrete.

It is also confirmed by the *K-S* test that the probability distribution of average compressive strength of the buildings and standard deviations fall into a normal distribution, and the *CV* takes a form of logarithmic normal distribution.

Compressive strength with reference to design strength

The design strength of the inspected buildings falls into two major groups, F_c=*18.0 MPa* and F_c=*21.0 MPa*, which will be dealt with in this paper.

Frequency distribution of average compressive strength and *CV* of cores in buildings of F_c=*18.0 MPa* are shown in Figure 4 and those in buildings of F_c=*21.0 MPa* are shown in Figure 5. The variation of average compressive strength in buildings of F_c=*21.0 MPa* is significant, as shown in Figure 4(a) and 5(a), which may be attributed to any differences in quality control manner by site associated with the higher design strength. On the other hand, *CV* of compressive strength in a building of design strength F_c=*21.0 MPa* as shown in Figure 4(b) and 5(b) is less than that of F_c=*18.0 MPa*.

Since the average core compressive strength of each building is normally distributed, it is possible to calculate a probability of the average compressive strength μ with respect to the design strength F_c. For buildings of F_c=*18.0 MPa*, probability of μ to be less

Changes in compressive strength by the completed year of buildings

Relations of average compressive strength of buildings and *CV* with respect to their completed year are shown in Figure 6. Relationship between average compressive strength and completed year of the building shows gently sloped linear correlation implying gradual increase of concrete strength with completed year. The lowest value of the average compressive strength began to increase gradually in 1970's and subsequently building with average strength lower than *12.5 MPa* cannot be found.

On the other hand, *CV* and the completion date of the building show negative linear correlation implying gradual decrease in variations of concrete strength as their completion date become younger. The highest value of *CV* began to decrease gradually in 1965's and other values fall into a range between *0.08* and *0.25*. This may be attributed to a wide spread use of concrete pumps and ready-mixed concretes.

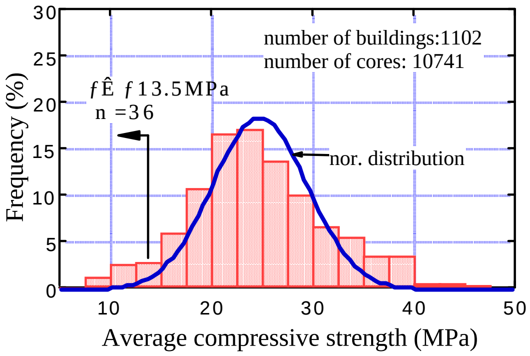


Figure1: Frequency distribution of each average compressive strength of all buildings

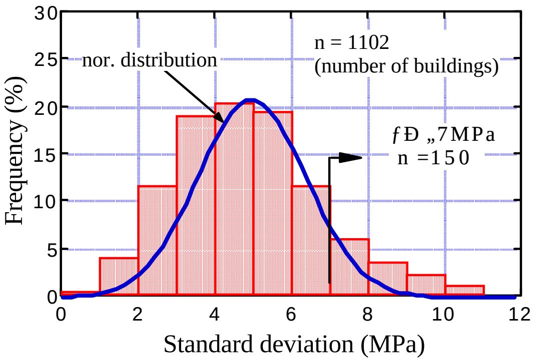


Figure 2: Frequency distribution of each standard deviation of all buildings

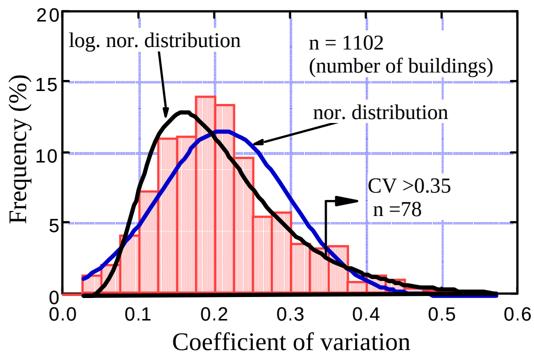


Figure 3: Frequency distribution of *CV* of compressive strength for all buildings

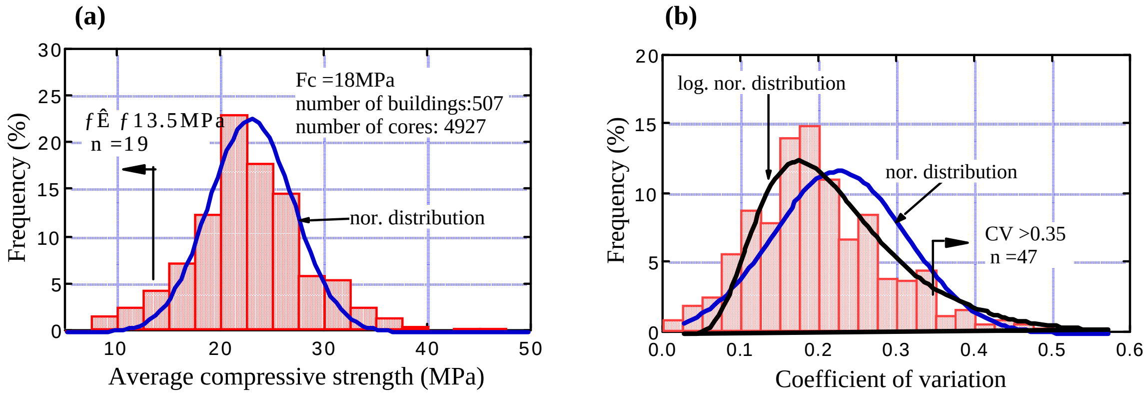


Figure 4: Frequency distribution of average compressive strength and *CV* of cores in buildings of *Fc=18.0 MPa*

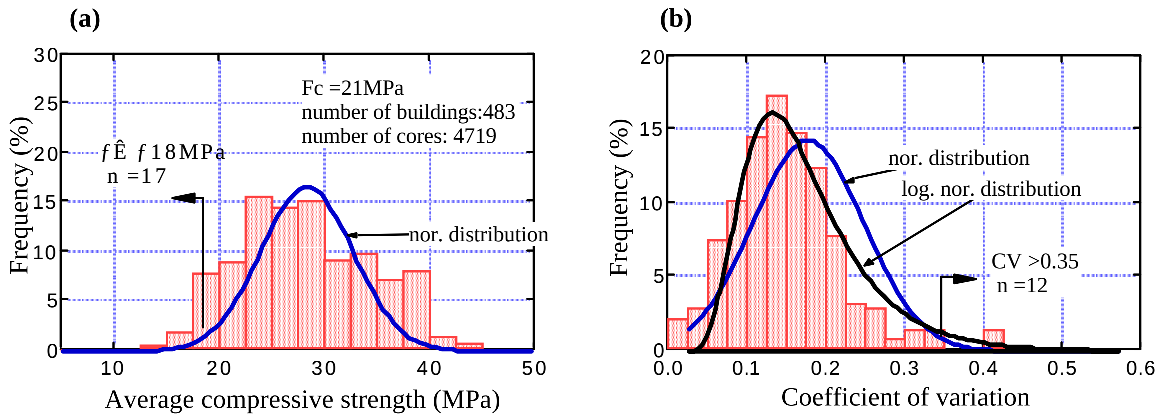
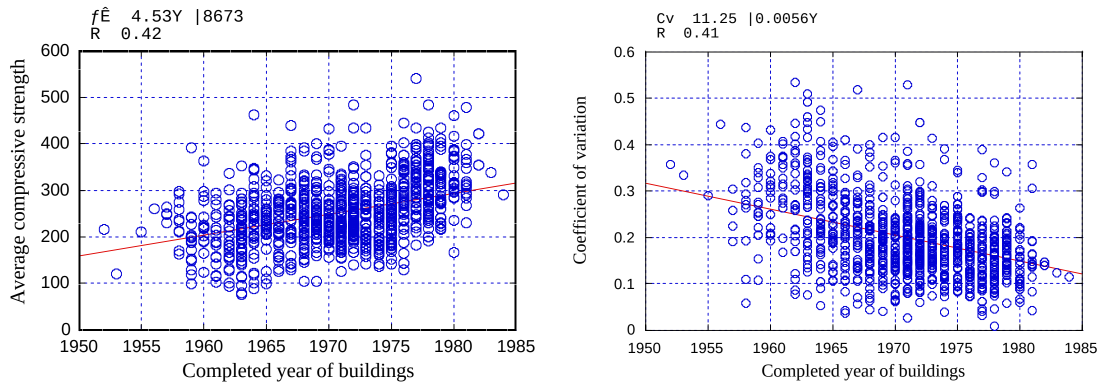


Figure 5: Frequency distribution of average compressive strength and *CV* of cores in buildings of *Fc=21.0 MPa*

than F_c is *15 %* while it is *12 %* for buildings of F_c*=21.0 MPa*. Therefore within the number of buildings inspected, buildings with design strength of *18.0 MPa* tend to have larger percent defective.



(a) Average compressive strength **(b) Coefficient of variation**

Figure 6: Relations of average compressive strength of buildings and coefficient of variation with respect to their completed year

Distribution of compressive strength in a building

Among all inspected buildings, *44* buildings provided more than *20* cores per one building, and typical frequency distributions of compressive strength in four buildings are shown in Figure 7(a)-(d). The distribution types are logarithmic normal distribution rather than normal distribution, where the peaks shift to the lower range, show keen increase and decrease gently to the higher side.

After executing chi-square test and *K-S* test for both distribution types, chi-square test was able to approximate both distributions but *K-S* test was only able to approximate the logarithmic normal distribution, thereby the distribution of core compressive strength in a building is found to be in logarithmic normal distribution.

Difference in compressive strength in a building by story

For buildings with sufficient amount of cores, average compressive strength and the standard deviation showed significant difference by story in spite of being built in the same building and the same design strength. Figure 8 shown some typical examples. This implies that the seismic diagnosis should be taken into account of the difference in compressive strength by story.

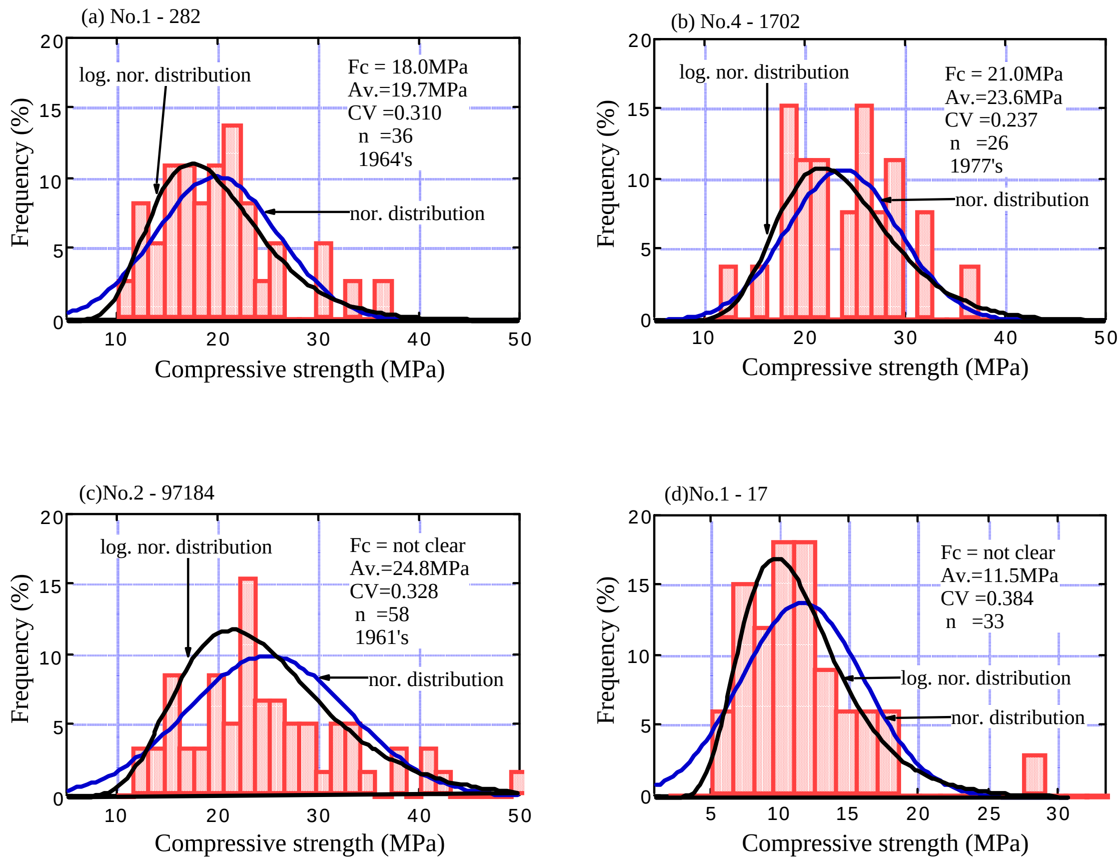


Figure 7: Typical frequency distributions of compressive strength

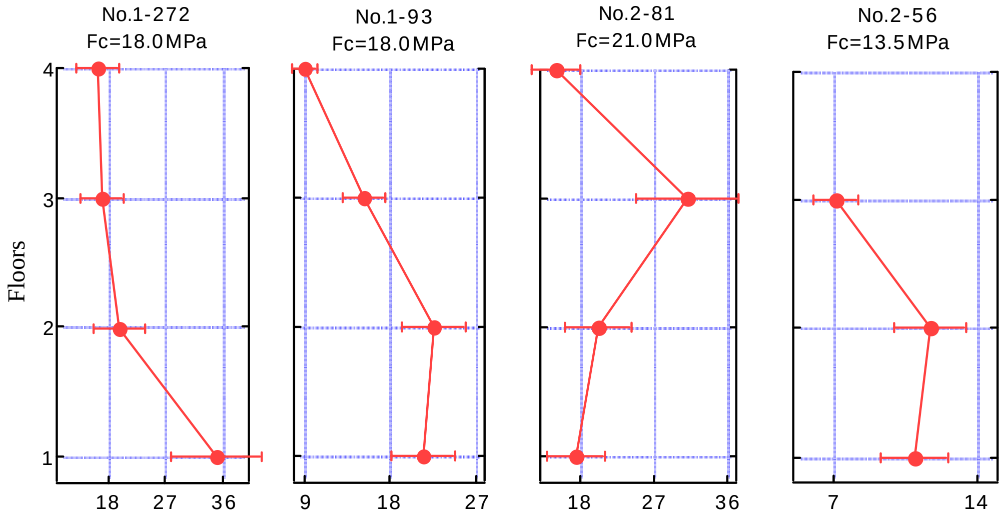


Figure 8: Compressive strength in different floors

PREDICTION OF STANDARD DEVIATIONS OF COMPRESSIVE STRENGTH IN STRUCTURES

In order to estimate accurately compressive strength of existing buildings for seismic diagnosis, as many numbers of cores as possible should be sampled but, in reality, concrete strength had to be estimated from limited number of core samples. We will classify measured compressive strength by design strength and by the date of completion in every five years, calculate the *CV* of compressive strength in this range and predict the standard deviation on the basis of the *CV*.

The *CV* of concrete core compressive strength in each range of buildings are shown in Table 3, which was prepared to have a rough figure of standard deviation based on the limited number of core samples. As an extreme case, only one compressive strength with a core sampled from a story of a building may be taken as an average strength μ_{test}, and the standard deviation of compressive strength σ of the story may be given by a product of μ_{test} and known *CV*. As shown in Table 3, the larger the compressive strength becomes or the younger the age of buildings are, the *CV* and the variation of concrete strength become smaller.

CONCLUSIONS

A statistical analysis is presented dealing with compressive strength of cores sampled from existing building structures, which were inspected for the purpose of seismic diagnosis. Major findings are as follows.

(1) Considerable numbers of buildings with low strength concrete were found in existing buildings and the variations of strength were significant.
(2) Buildings of recent completion showed larger strength and smaller *CV*.
(3) Buildings designed in a higher concrete strength showed stable concrete quality with less variation in strength.
(4) Probability distribution of average compressive strength of the buildings falls into a normal distribution, while the *CV* takes a form of logarithmic normal distribution.
(5) Even only limited number of cores are available on the seismic diagnosis of existing buildings, prediction of a probable standard deviation of concrete strength is still possible using the data shown in Table 3

Table 3: The coefficient of variation of concrete core compressive strength in each range of buildings

Fc (MPa)	13 , 13.5 (MPa)	15 (MPa)	17 , 18 (MPa)	21 (MPa)	22.5 , 24 (MPa)	Total (including Fc are not clear)
Beofre 1961's Period‡ T	n (core)=44 n (buildings)=5 CV=0.364	n (core)=69 n (buildings)=9 CV=0.309	n (core)=250 n (buildings)=27 CV=0.250			n (core)=453 n (buildings)=52 CV=0.268
1961's 1965's Period‡ T	n (core)=25 n (buildings)=3 CV=0.311	n (core)=61 n (buildings)=9 CV=0.268	n (core)=1423 n (buildings)=138 CV=0.269	n (core)=44 n (buildings)=6 CV=0.233		n (core)=1769 n (buildings)=173 CV=0.271
1966's 1970's Period‡ T		n (core)=3 n (buildings)=1 CV=0.234	n (core)=1965 n (buildings)=205 CV=0.205	n (core)=395 n (buildings)=36 CV=0.165		n (core)=2530 n (buildings)=260 CV=0.198
1971's 1975's Period‡ U	n (core)=22 n (buildings)=3 CV=0.202	n (core)=12 n (buildings)=1 CV=0.235	n (core)=1180 n (buildings)=128 CV=0.191	n (core)=2097 n (buildings)=202 CV=0.189	n (core)=13 n (buildings)=1 CV=0.186	n (core)=3398 n (buildings)=344 CV=0.189
1976's 1980's Period‡ U			n (core)=50 n (buildings)=5 CV=0.146	n (core)=1950 n (buildings)=211 CV=0.155	n (core)=26 n (buildings)=2 CV=0.166	n (core)=2086 n (buildings)=224 CV=0.156
After 1981's Period‡ U				n (core)=159 n (buildings)=18 CV=0.157		n (core)=178 n (buildings)=21 CV=0.156
Total (including buildings which completed year are not clear)	n (core)=91 n (buildings)=11 CV=0.304	n (core)=157 n (buildings)=21 CV=0.282	n (core)=4938 n (buildings)=511 CV=0.221	n (core)=4738 n (buildings)=483 CV=0.171	n (core)=39 n (buildings)=3 CV=0.173	n (core)=10741 n (buildings)=1102 CV=0.201

ACKNOWLEDGEMENT

A part of this research is carried out with the financial support of Grant in Aid for Scientific Research from the Japanese Ministry of Education, Science and Culture. This support is thankfully acknowledged.

REFERENCES

Masuda Y., Tomosawa F. and Yajima Y. (1982), "Concrete Quality in Existing Reinforced Concrete Building (Part1) Compressive Strength in Each Building", *Journal of Structural and Construction Engineering*, 311, 1, pp.153-162

Masuda Y., Tomosawa F. and Yajima Y. (1982), "Concrete Quality in Existing Reinforced Concrete Building (Part2) Concrete Qualities by Element of Building and by Stories", *Journal of Structural and Construction Engineering*, 317, 7, pp.155-163

Shimizu Y. and Hirosawa M. (1997), "A Study on the Concrete Strength in Existing Reinforced Concrete Buildings", *Proceeding of Symposium on the Technologies for the Earthquake-proof Concrete Buildings*, pp.1-10 Zhou J.D., Hirosawa M. and Shimizu Y. (1998), "Statistical Analysis of Concrete Strength in Existing Reinforced Concrete Buildings