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Invited paper

Multi-Scale Review for Possible Mechanisms of Natural Frequency Change of Reinforced Concrete Structures under an Ordinary Drying Condition

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Abstract

Based on a review from a view point of multi-scale perspective, it is concluded that possible mechanisms of natural frequency change of concrete structures under an ordinary drying condition are reduction of Young’s modulus of concrete and stiffness reduction of reinforced concrete member due to shrinkage-induced cracking. Both two mechanisms can be provoked by drying, which is natural environmental condition for all the building structures. This natural frequency change is important for the integrity analysis of nuclear power plants because seismic response change and sympathetic vibration between structure and installed implementations are expected. In addition, to understand the mechanism this mechanism should contributed to post-earthquake integrity evaluation which is necessary to efficient and continuous operation of nuclear power plants. The lost parts of scientific knowledge and needs of experimental data for whole picture of this natural frequency change have been pointed out.

1. Introduction

Aging management of concrete structures becomes important issue in contexts of economy and environment. It has been reported that the life of architectural reinforced concrete building in Japan is about 50 years (Komatsu 2008), and this value is significantly smaller than that in Europe or US (Komatsu 2000). This short life of dwellings in Japan has large impact on environment through material waste, natural resource consumption, and CO₂ emission, and design and maintenance of long-life dwellings are desired in Japan.

With regards to civil infrastructures in Japan, they were originally designed without any expected life-span, and they were mainly built from 60’s to 80’s, while currently many deteriorations have been reported (Kobayashi 2000). About 30% of civil structures have passed more than 40 years, for this reason, significance of monitoring, maintenance, prediction, and integrity evaluation is emphasized recently and based on these background as well as the impacts of Great East Japan Earthquake on Japanese society, new act was enacted (Japanese government 2013).

Industry plants are also in the same way. They are required the proper aging management. As for nuclear power plants in Japan, in addition to the economical benefit, they are also required to keep the integrity and safety.

Recently, a new phenomenon of structural performance change of concrete structures has been spotlighted, that is natural frequency. Here, possible mechanism of the natural frequency change is discussed through a view of multi-scale characteristic of concrete. In addition to the natural frequency change, impact of drying on concrete structure through concrete properties change, which has not been cleared, is discussed for aging management of concrete structure for nuclear power plants.

2. Facts of natural frequency of the concrete structures.

Kashima and Kitagawa (2006) have reported a natural frequency change of 8-story steel reinforced concrete (SRC) building, by collecting the data by densely instrumented with 22 accelerometers during small and medium-sized earthquakes. The data is analyzed by using Evolution Strategy to optimize analysis parameters for a multi-story sway-rocking model. And 18% decrease in natural frequency of building after 7 years after construction was discovered. Li et al. (2014) also use the data from the same system but the analysis is expanded to 14 years after construction, and 45% reduction of natural frequency was found including the damage during the Great East Japan Earthquake. It should be noted that all the earthquakes except for the Great East Japan Earthquake shows no change of stiffness during the earthquakes.

Toyobe et al. (2013) have collected the data of accelerometers implemented in the buildings and they found time-dependent behavior of natural frequencies of buildings. After 8 years of construction, 20% decrease in natural frequency was observed in case of 7-story SRC building, while the reduced value was 33% in case of reinforced concrete (RC) building. It has been also reported that the 4-story RC structure after 40 years of construction did not show any reduction of natural frequency change. Therefore, this tendency can not be at-

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tributable to the soil-structure interaction problem solely unlike the cases found in European buildings.

In case of nuclear power plant, Unit No.1 of Onagawa Nuclear Power Plant has been analyzed since 1985, and they found the continuous reduction of natural frequency of the plant and it was 22% after 25 years of construction. This means that even the RC members are thick enough, it has a natural trend to decrease the stiffness of the members (Nuclear and Industrial Safety Agency 2011; Ogata et al. 2011). In addition to this phenomenon, there were some cases that the natural frequency showed sudden drop during or after the earthquakes but there is some recovering mechanism and it turned back to the natural decreasing trend. Similar phenomenon have been reported by Saito (2012). In case of very large size of earthquake, it is possible that this recovering mechanism can not bring the frequency back to the natural trends (Takahashi et al. 2012; Uebayashi and Nagano 2012). Summary of natural frequency of concrete related buildings are shown in Fig. 1.

Based on these previous researches, it is concluded as follows; almost all the reinforced concrete structures show decrease of natural frequency and this attributes to the reduction of stiffness of concrete structure, because there is little difference of mass of structure during the monitoring in some cases. Consequently, there is a common environmental condition which cause reduction of stiffness of reinforced concrete member, and two mechanisms for reduction of stiffness of reinforced concrete member are derived; reduction of Young’s modulus of concrete and cracking in reinforced concrete member. Now, the common environmental condition, drying, is discussed to emphasize the importance of scientific research for prediction of performance of concrete structures to contribute to aging management of concrete structures. The whole structure of the manuscript is shown in Table 1.

3. Concrete components and concrete

3.1 Cement paste properties under the first drying

Hardened cement paste (hcp) made from cement paste with relatively high water cement ratio (W/C = ~0.55) has notable colloidal nature. This nature is attributed to calcium silicate hydrate (C-S-H) with low crystallinity which is hydration product of alite and belite. There are many alibi of the colloidal nature of C-S-H. For example, BET surface from nitrogen sorption isotherm (Tomès et al. 1957; Hunt et al. 1960; Parrott et al. 1980; Litvan and Myers 1983), water vapor sorption isotherm (Tomès et al. 1957; Maruyama et al. 2014a), and surface area obtained by SAXS (Winslow and Diamond 1974; Kropp et al. 1985; Völkl et al. 1987) are affected by long-term drying.
condition. A shape of water vapor sorption isotherms is also dramatically affected by the drying (Maruyama et al. 2014a). It has been reported that irreversible shrinkage after the first drying is large when W/C of paste is large (Helmuth and Turk 1967). A part of these phenomena is considered to attribute to the low density (LD) C-S-H, which is quantitatively proposed by Tennis and Jennings (2000). A picture obtained by field emission (FE) scanning electron microscopy (SEM) of hydrated cement paste is shown in Fig. 2. In this picture, the low density C-S-H is clearly confirmed in white Portland cement paste with W/C = 0.55 and it is produced outer area of original boundary of cement particle. This LD C-S-H is almost similar definition of that of outer product firstly addressed by Goto et al. (1976).

This LD C-S-H is believed to shrink and be compacted by drying and the nitrogen accessible area is reduced. A morphology change of LD C-S-H is observed by environmental SEM (Fonseca and Jennings 2010) and this is also reproduced by FE-SEM as they were shown in Fig. 3. In wet condition, LD C-S-H has indeterminate morphology while it has fibrillar shape in the sample slowly dried under 40% RH for 1.5 years. These observations clearly show the dynamic microstructural change in hardened cement paste under the first drying process. And thus, cement paste has a colloidal nature (Jesser 1927; Tomes et al. 1957; Jennings 2000, 2008).

Based on these facts, modulus of elasticity and shrinkage strain of hardened cement paste should cause the change of Young’s modulus and volume of concrete.

Sereda et al. (1966) substantially studied the relation between relative humidity and Young’s modulus of hcp, but they focused mainly on the Young’s modulus change after strongly dried condition and avoided to discuss about the unstable calcium silicate hydrate under the first desorption process because their objective is to clarify the role of well-stabilized calcium silicate hydrate in cement paste. Wittmann (1973) showed the Young’s modulus change of hardened cement paste under the first desorption process and it showed concave curve in the relationship between relative humidity and Young’s modulus, and the minimum value was observed around 30 ~ 40% RH. The variation was within 18% of the Young’s modulus at the saturated state. This Young’s modulus is obtained by compressive loading test.

In our previous experiments (Horiguchi et al. 2011; Maruyama et al. 2014a), similar trends are confirmed by using the cement paste made from white cement by bending test and cement paste made from white cement and ordinary Portland cement by ultrasonic pulse velocity measurement. The summary is shown in Fig. 4. In case of Young’s modulus determined by bending test and ultrasonic pulse velocity measurement, they show 50% and 25% variation under the first drying, and around 40 ~ 50% RH the minimum values were observed. It should be mentioned that there is a discrepancy in the range from 100% to 80% RH between bending test data shown in Fig. 4 and ultra-sonic measurement results or Wittmann (1973).
The results of compressive test or ultrasonic measurement test might be reflected by the load bearing water molecules in the cement paste while they will not bear the stress in tension case. This is a possible explanation for the discrepancy.

With regards to the Poisson’s ratio, it has decreasing trend as a function of relative humidity. ~0.23 is the value under dried state, while it is about 0.26~0.28 in saturated state as shown in Fig. 5. These trend might be explained by the change in agglomeration of C-S-H and atomic crystal structure of C-S-H, which are still under discussing. Small angle scattering profiles (Chiang et al. 2012, 2013; Nicoleau et al. 2013; Traptote-Barreira et al. 2015) and 1H-NMR relaxometry (Korb 2009; McDonald et al. 2010; Muller et al. 2012, 2013, 2015; Valori et al. 2013) give insights on this topic. An example of elaboration to explain the relationships between C-S-H microstructure change under the first drying and physical properties is shown in the references (Maruyama et al. 2014a, 2015, 2016a).

Drying shrinkage of cement paste might have large impact on concrete property, because large shrinkage difference is expected in concrete and cracks in cement paste around aggregates are going to be produced under drying (Pickett 1956; Hansen and Nielsen 1965; Hobbs 1974; Grassl et al. 2010; Idiart et al. 2011; Lagier et al. 2011; Zhang et al. 2013; Maruyama and Sasano 2014), while the mechanism of shrinkage of hcp is not clarified (Powers 1965; Helmuth and Turk 1967; Feldman and Sereda 1968; Wittmann 1968; Bažant 1972; Beltzung and Wittmann 2005; Setzer 2007; Wittmann 2008; Beaudoin et al. 2010; Maruyama 2010). The most lost part is irreversible shrinkage of hcp under the first desorption process. In author’s previous study (Maruyama 2010), shrinkage of hcp is well-predicted by the statistical thickness of water vapor adsorption based on a disjoining (or hydration) pressure theory. This indicates that a number of water molecules adsorbed on the C-S-H is the key parameter for drying shrinkage of hcp including irreversible shrinkage. In Fig. 6 drying shrinkage (a) and water content (b) of matured hcp 3 mm-thick specimens dried slowly for 0.5 year are shown including re-humidifying process (Maruyama 2010). There is a clear hysteresis above 40% RH in both length-change and long-term water vapor sorption isotherms. In addition to these data, water vapor BET area (\(S_{BET}\)) of hcp samples was obtained by sorption isotherms by volumetric method. Then the relationship between incremental statistical thickness of adsorption (origin is saturated condition) and drying shrinkage strain above 40% RH is plotted in Fig. 6 (c). As it is shown, clear linear relation is obtained disregards to water to cement ratio. The range of 100% to 40% RH is corresponding to the range where the irreversible shrinkage is observed (Helmuth and Turk 1967; Maruyama et al. 2015), and it
was suggested that another shrinkage mechanism is active rather than surface energy shrinkage mechanism in this range (Maruyama et al. 2015), and concerning this another shrinkage mechanism, statistical thickness of adsorption is the key parameter.

Now, the important issue for long-term properties change of hcp is laid in the first drying process, and it is related to colloidal behavior and atomic-scale structural change of C-S-H. All the phenomena related water content change under drying can be interpreted different ways as shown in Fig. 7. In the previous models, C-S-H is considered to have the fixed interlayer distance and water sorption process in the interlayer space is saturated under 11 ~ 30% RH. This assumption is based on an interpretation by Brunauer et al. (1967) from water vapor sorption isotherms. However, it is possible that distance of C-S-H mono layers and number of adsorbed water in this space depend on the drying process. Previous papers (Maruyama et al. 2015, 2016a) proposed a hypothesis that there is a movable C–S–H monolayer and the distance between the C–S–H monolayers is dynamically changed by drying and re-humidifying. Because there is no structural limitation in maintaining the distance between C–S–H monolayers, such as Si-Q3 sites which should be a role of pillar to fix the distance between CaO layers, and randomly attached silicate dimers on the CaO layer should inflect the structure, crystal growth in the 002 direction is difficult (Gartner 1997). In addition, water sorption process should be initiated in the space surrounded by C-S-H monolayers, because surface potentials from each C–S–H monolayer are overlapped. These structural characteristics must change the distance between C–S–H monolayers during the sorption process like montmorillonites (Cases et al. 1992). In other words, gel water is re-interpreted as interlayer water in movable C-S-H monolayers.

Complete picture of C-S-H contributes the time dependent properties change of concrete structures under drying, further investigations are required for this purpose.

3.2 Aggregate behavior under the first drying
Aggregate generally occupied about 60~70% of volume of normal strength concrete. Therefore, the property of aggregate has a large impact on mechanical performance of concrete. Generally, the chemical and physical stabilities for required property as a concrete aggregate are evaluated by national or international standard before concrete mixing, however, still many variations are possible. One of them the shrinkage performance of aggre-

**Fig. 6** (a) Shrinkage strain of ordinary Portland cement paste with water to cement ratio of 0.55 (N55), 0.40 (N40), and 0.30 (N30). (b) Water content in hcp for N55, N40, and N30. (c) Relationship between incremental statistical thickness of adsorption and drying shrinkage of concrete structures under drying.
gate is not fully checked. Drying shrinkage of concretes which were made by Japanese design for mixture proportion showed high correlation of shrinkage of coarse aggregate (Fujiiwara 2008). The example is shown in Fig. 8 made from the data by Horiguchi et al. (2011) and Teranishi et al. (2011). From this aspect, the inherent shrinkage property of aggregate is significant. In our previous study, shrinkage of sandstone aggregates available in Japan is found to be a function of amount of chlorite which was formed in diagenesis (Igarashi et al. 2015), as it is shown in Fig. 9. This is because chlorite forms in matrix located between quartz or feldspar grains and the clay minerals can shrink without large restraint by the grains. The relationship between mineral composition of aggregate and physical properties are important issue for aging management of concrete.

Particle size and its distribution, and interfacial zone will be treated in the next section through restraint performance for shrinkage of mortar or cement paste.

3.3 Young’s modulus, shrinkage, and creep of concrete under the first drying

Shrinkage strain of matured mortar is more than 5 times as large as that of aggregate, and Young’s modulus of mortar is less than quarter of that of aggregate (Maruyama et al. 2014b). Consequently, large tensile stress is produced in mortar of concrete under the first drying process brought by the restraint roll of coarse aggregate and cracks can be formed around coarse aggregate (Carlson 1938; Hansen and Nielsen 1965; Hobbs 1974; Bisschop and van Mier 2008; Idiart et al. 2011; Maruyama and Sasano 2014). The width of cracks formed around aggregate becomes wider as mortar shrinks. Therefore, the crack opening volume accumu-

![Diagram](image1)

**Fig. 7 Comparison of (a) Feldman and Sereda microstructure model (Feldman and Sereda 1968) and (b) Proposed model in which water is trapped between calcium silicate mono layers and their distance and number of trapped water molecules are dramatically changed under the first desorption process (Maruyama et al. 2015).**

![Diagram](image2)

**Fig. 8 Relationship between shrinkage of coarse aggregate and that of concrete (Horiguchi et al. 2011; Teranishi et al. 2011).**

![Diagram](image3)

**Fig. 9 Relationship between shrinkage strain of sandstone aggregate and amount of chlorite (Igarashi et al. 2015).**
lated in concrete is a function of the difference of shrinkage strain between mortar and coarse aggregate. The increase in voids in concrete reduces the Young’s modulus of concrete because load bearing area is reduced (Maruyama et al. 2014b) (see Fig. 10). Resultantly, difference of shrinkage between concrete and mortar represent the volume of accumulated spaces by opening of cracks around aggregate. Therefore, the reduction ratio of Young’s modulus of concrete after drying has linear relation with the difference of shrinkage between concrete and mortar as it is shown in Fig. 11. With this regards, shrinkage of coarse aggregate is related to the reduction of Young’s modulus through restraint role to the mortar shrinkage. Shrinking aggregate has a smaller restraint role. As it is seen in Fig. 10, concrete with shrinking sandstone showed less reduction of Young’s modulus after drying.

Consequently, Young’s modulus change of concrete is tightly related to the shrinkage of concrete and mortar. There are plenty of researches on relationship between concrete shrinkage and mixture proportion, therefore, some important notes are addressed here.

Relationship between the shrinkage of mortar and the shrinkage of cement paste is not fully understood. Because the shrinkage of mortar is only a function of volume of aggregate (Fig. 12) and not the size of aggregate (Thierry et al. 2008; Sakaida et al. 2014) while, the size of coarse aggregate has a large impact on shrinkage of concrete (Carlson 1938; Maruyama and Sasano 2014). This phenomenon can be partially explained by a role of interfacial transition zone (ITZ) formed between cement paste matrix and aggregate (Neubauer et al. 1996; Maruyama and Sugie 2014) but the restraint role of small grains on the shrinkage of paste remains to be solved.

ITZ is a one of the key factor of concrete property. It is

![Fig. 10 Ratio of Young’s modulus of concrete / mortar / paste after drying to the Young’s modulus of concrete at sealed condition (E/Eo). Each specimen reached an equilibrium in drying environment after 0.5 ~ 1.0 year. Limestone aggregate was very pure and has almost no shrinkage property, while sandstone had large amount of chlorite and shrunk much. Mortar has the same type and volume of fine aggregate as that of concretes. Concrete and mortar was made by high early strength Portland cement and paste was made from white cement. Details are shown in Maruyama et al. (2014a) and Maruyama et al. (2014b).](image1)

![Fig. 11 Ratio of Young’s modulus of concrete affected by drying to that of concrete under sealed condition (Ec/Eco) as a function of difference of shrinkage between mortar and concrete.](image2)

![Fig. 12 Shrinkage of paste and mortar with different fine aggregate volume and sizes (Sakaida et al. 2014).](image3)
possible to explain the shrinkage of concrete affected by the aggregate size by using the presence of ITZ (Maruyama and Sugie 2014). The large size of aggregate reduces the shrinkage of concrete. ITZ is generally considered to be produced by the “wall effect” of the cement particle packing process on the surface of the aggregate (Scrivener et al. 2004). And the weak property on the surface of aggregate is believed by the facts of porosity distribution findings (Breton et al. 1993; Scrivener et al. 2004; Cwirzen and Penttala 2005; Herve et al. 2010), an SEM analysis (Scrivener and Gartner 1988; Scrivener et al. 2004), and physical properties testing (Xie et al. 1991; Ping and Beaudoin 1992; Mitsui et al. 1994; Ollivier et al. 1995; Hearing 1997). As the porosity in the ITZ is more than three times that of normal mortar located far from the surface of the aggregate (Scrivener and Gartner 1988; Scrivener et al. 2004), resistivity to shrinkage of mortar matrix is low. Therefore, even there is a report that the thickness of ITZ depends on the size of aggregates (Xie et al. 1991; Ollivier et al. 1995; Tasong et al. 1999; Rao and Raghu Prasad 2004), the resistivity of aggregate to the shrinkage of mortar matrix can be evaluated by the ratio of thickness of ITZ to the radius of aggregate. The larger size of aggregate has a large restraint role to the mortar shrinkage, while the smaller size of aggregate has a small restraint role. And this large restraint role is undeniably related to the reduction of Young’s modulus.

Reduction of Young’s modulus also contributes to the increase of creep under the drying. Larger creep coefficient under the drying environment than that of concrete without any moisture exchange with environment is known as Pickett effect (Pickett 1942). If creep is inherent nature of cement paste, creep strain at the cement paste in concrete should be definable. Therefore, this phenomenon should be explained by the structural nature. One is the structural condition of mortar and coarse aggregate. Shrinkage strain of cement paste is larger than the average creep strain of concrete specimen. This leads that cracks are formed around aggregate and reduction of Young’s modulus of dried part of concrete is observed even under the sustained load. This reduction of Young’s modulus increase the elastic strain under the drying condition as it is shown in Fig. 13. This is different from the concept proposed by Neville and Meyers (1964). In case of Young concrete and concrete block with a large section, the Neville’s model is applicable, but in matured stage, the impact of increase in Young’s modulus due to additional hydration after demolding can be negligible and drying impact may overcome it. To confirm this, the components of creep coefficient is evaluated by using the data reported by Raymond and Harmer (1931) in Fig. 14.

In Fig. 14 right, reduction of Young’s modulus, which is based on the Fig. 10 is considered for one of the creep coefficient component. It should be noted that this assumption is applicable only to the condition under the equilibrium, and this is due to re-distribution of stress in concrete under equilibrium condition. Schematic stress re-distribution in concrete is shown in Fig. 15(a). The residual components is caused by stress concentration mechanism after drying. One is based on material characters. After formation of cracks around aggregate, stress bearing passes are limited and resultanty, the stress per unit area of cement paste in concrete is increased and creep behavior is enhanced due to this stress localization. The other is observed in member size. After drying, surface part of concrete exhibit larger shrinkage than inner concrete. Therefore, the stress is re-distributed and localized in central part of concrete (shown in Fig. 15(b)). The peripheral concrete part shows shrinkage rather than creep, therefore, the creep behavior should be governed by central part concrete. This consequence indicates that measurement procedure of creep deformation, especially in position, needs special care and drying creep is structural performance and not material performance.

![Fig. 13 Schematic of creep coefficient components of matured concrete proposed by Neville (A) and proposed concept (B).](image-url)
4. Impact of volume and Young’s modulus change of concrete on RC member performance

Shrinkage of concrete induces stiffness of reinforced concrete structure (Okada et al. 1986), and it decrease in a flexural cracking moment and increase in curvature and maximum crack width of beam (Tanimura et al. 2007; Maruyama and Teshigawara 2010). This is explained by tensile stress of concrete induced by shrinkage restraint and strain difference before and after cracking of concrete. From this regards, creep strain of concrete in RC column under axial load has the same role as that of shrinkage. Creep strain and shrinkage strain in column make re-distribution of stress among concrete and rebars, and in case of un-loading process such as seismic response, crack is easily produced in tension (Komuro et al. 2008). This re-distribution of stress caused by shrinkage also reduces the moment capacity at the failure of cover concrete (Collins et al. 1993). Releasing of compressed stress of rebar due to concrete shrinkage restraint causes the additional bending movement and crack opening. In addition, deflection at the moment capacity at failure of concrete is increased by creep strain based on our preliminary experiment for impact of sustained load on total stress-strain curve of concrete shown in Fig. 16.

A diagonal cracking moment of RC beam as well as a shear capacity of RC beam is also affected by shrinkage (Maruta and Yamazaki 1990; Katayose et al. 2006; Sato and Kawakane 2008; Gebreyouhannes and Maekawa 2011). This is simply because the stress, position, and direction of diagonal cracking are altered by shrinkage-induced stress and enlarged crack width. The wider diagonal cracks also affect the performance of RC column, the loading capacity in cyclic loading process after opening of diagonal cracking is decreased by this width of diagonal cracks (Maruyama et al. 2011).

Decreasing of Young’s modulus of concrete leads reduction of stiffness of RC member. In addition, shrinkage induced cracking has a large impact on stiffness of RC member. It should be noted that the both two impacts are brought by the shrinkage of cement paste in concrete mainly. One is by way of cracks around aggregate and they are almost invisible, and the other is by way of visible cracks which are localized cracks due to restraint of concrete by rebars or outer structure. This difference is induced by aggregate and its ITZ performance. Concrete containing (pure) limestone coarse aggregate is known to reduce the shrinkage-induced visible cracking (Mitani et al. 2016), but this concrete showed relatively large decrease in Young’s modulus of concrete under drying (as it is shown in Fig. 10). This is the trade-off relationship (Maruyama et al. 2016b). To compare the impacts of decrease in Young’s modulus and shrinkage-induced cracking, simplified numerical analysis has been conducted (Sugie et al. 2014). The calculation was made by 2-dimensional finite element method (FEM). The target RC wall is shown in Fig. 17. In this moisture transfer at 20 degree Celsius and 60% relative humidity was conducted (Maruyama and Igarashi 2015) and then relationship between water content and concrete shrinkage (Maruyama et al. 2014b) is used for input of shrinkage.
age-induced stress calculation in concrete structure. Shrinkage strain is considered as equivalent nodal force to this system. In addition to this, Young’s modulus change of concrete is considered by using the relationship between water content and Young’s modulus of concrete (Maruyama et al. 2014b). In FE-analysis, cracks are considered as smeared model. The results of structure made from concrete containing limestone are shown in Fig. 18(b). The reduction of stiffness (Fig.18(a)) as well as typical calculated cracks in concrete wall (Fig. 18(b)) is shown. Behavior of structure made from concrete containing limestone is compared with that from concrete containing shrinking sandstone concrete and the results are shown in Fig. 18(b).

In Fig. 19, the ratio of natural frequency to that without drying is estimated under the condition that there is no mass change, and the primary mode is intended. Figure 19 indicated that the shrinkage-induced cracking has larger impact than that of decrease in Young’s modulus due to drying. Based on the comparison with a record of Onagawa NPP-3, the reduction trend obtained by FE-analysis seems comparable to that of real record and it suggests that the reason of stiffness reduction of real concrete structure is caused by drying environment.

5. Discussion for aging management

Based on the review, it is highly possible that the natural frequency change is caused by reduction of Young’s modulus and shrinkage-induced cracking in reinforced concrete member due to drying, in addition to the damage during earthquake. This natural frequency change may have impact of seismic load of the member in NPP as well as sympathetic vibration between building and instruments, such as piping system, cable support system, turbine, and other implementations installed in NPP buildings. Even the wide range of target frequency is considered in the design state, it is important to consider the risk of base line trend of natural frequency. In case of high-rise building or structure, secondary or other modes should be considered.

The base line trend is also crucial to evaluate the damage during the earthquake. Although many monitoring sensors, such as accelerometer and velocimeter, are installed to analyze the performance curve (displacement versus load) of the structure, damage due to seismic response can not be identified without baseline trend due to drying. These sensors and obtained analysis results should contribute to post earthquake performance evaluation of the structure for efficient operation of NPP. To develop the automated system for post earthquake integrity analysis, the mechanism of natural frequency change and its prediction are necessary. It should be noted that the strength and Young’s modulus of concrete has no longer strong correlation after matured state (Maruyama et al. 2014b), because drying condition changes strength and Young’s modulus of concrete by different mechanisms. Direct evaluation of Young’s modulus of concrete is desired, but using the...
data obtained from core-sample needs special care, because massive concrete member has a distribution of water content and resultant Young’s modulus. In this sense, numerical evaluation might have potential to evaluate the average concrete stiffness.

The most important knowledge is that the reduction ratio of natural frequency after equilibrium and the rate of reduction of natural frequency to achieve the equilibrium. Because aging management is based on both integrity at the present state and in future until the target life span, those two parameters are crucial. Regarding the reduction ratio, it is possible to estimate the value by using drying shrinkage strain and Young’s modulus of concrete under the given environment which is equivalent to that in nuclear power plant. But the rate of reduction of natural frequency needs more scientific background of concrete under drying process. The first drying process in concrete is always accompanied with colloidal alteration of C-S-H, and this process is not considered in existing research and they always assume that concrete is just a porous material, resultantly, the drying process under high temperature or temperature gradient needs more data (Shire and Cheong 1988; England and Khoylo 1995; Lien and Wittmann 1998).

6. Summary

It is concluded that possible mechanisms of natural frequency change of concrete structures under an ordinary drying condition are reduction of Young’s modulus of concrete and stiffness reduction of reinforced concrete member due to shrinkage-induced cracking. Both two mechanisms can be provoked by drying, which is natural environmental condition for all the building structures. While the Young’s modulus change of concrete is neglected in the present design codes, it is possible that it shows more than 20% reduction in general drying condition. In addition, drying condition changes strength and Young’s modulus differently, it should be kept in mind that there is no longer correlation between strength and Young’s modulus of concrete in matured state, unlike young concrete. From this point of view, direct evaluation of Young’s modulus of concrete, but not from a calculation based on compressive strength and relationship between strength and Young’s modulus, is desired. Concrete, however, has a distribution in its properties in the reinforced concrete member under drying condition, therefore, data treatment of core-sample should take into account this nature of concrete member.

The natural frequency change is important for the integrity analysis of nuclear power plants because seismic response change and sympathetic vibration between structure and installed implementations are expected. Second mode of structure is a potential risk for sympathetic vibration of installed implementations. To understand the mechanism should contributed to post-earthquake integrity evaluation which is necessary to efficient and continuous operation of nuclear power plants by identifying the damage due to seismic response from baseline trend of natural frequency change as well as reduction of stiffness of structure.

The lost parts of scientific knowledge and desired experimental data to obtain the whole picture of the natural frequency change under ordinary drying condition have been pointed out.

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