Remainin Shear Capacity of Fire-Damaged High Strength RC Beams after Moist Curing

Kazuaki Higuchi¹, Keitai Iwama² and Koichi Maekawa³*

Abstract

This study presents an analytical method for estimating the remaining shear capacity of reinforced concrete (RC) beams subjected to high temperature heating and verifies it by experiments. We focused on the mechanism by which the remaining shear capacity of members self-recovers in a humid environment after slow cooling. The authors confirmed that the infiltration of water vapor in the air into concrete after heating caused rehydration of quicklime (CaO) produced by high-temperature heating and self-recovery of material strength. Based upon material experiments, the mechanical model of calcium hydroxide formation by rehydration of quicklime was incorporated into the multi-scale analysis. Using the proposed model of this study, the effect of damage on the remaining strength of damaged members was also investigated. It was confirmed that the series of high temperature heating, slow cooling, moisture absorption, self-healing, and remaining shear capacity could be reproduced by the multi-scale analysis.

1. Introduction

The functional shutdown of social infrastructure facilities due to fire has a significant impact on socioeconomic activities (Hoj et al. 1999; Hedden et al. 2010; JCI 2017). Even if collapse and functional shutdown as the result of a fire can be avoided, the remaining structural performance after the fire must be evaluated to allow rapid recovery. In the context of risk management of infrastructure facilities, a growing number of studies have been conducted in recent years to quantitatively assess structural performance during and after fires (Kodur and Agrawal 2016; Li et al. 2020; Shachar and Dancygier 2020; Shang et al. 2020; Hashim and Kadhum 2021).

Exposure of reinforced concrete (RC) structures to high temperatures increases the risk of spalling of near-surface concrete as has been shown in past studies, for example, Kalifa (2000, 2001) and Phan (2008). When cover concrete spalls, reinforcing bars are directly exposed to fire, and the stiffness and yield strength of the members decrease due to bond deterioration (Kodur 2003; Dwaikat and Kodur 2009; Shah and Sharma 2017). Although there have been many studies on spalling risk assessment, for example, those by Gawin et al. (2003, 2006, 2019), Zhang and Davie (2013), Zhang et al. (2017) and Sun et al. (2019), in order to quantify remaining shear capacity after progressive spalling, it is essential to evaluate material-level damage and member-level performance consistently.

The authors have expanded the scope of application of existing multi-scale analysis (Ishida and Maekawa 1999; Maekawa et al. 2003, 2008) to high temperature regions of about 1000°C (Iwama et al. 2018, 2019, 2020, 2021). This analysis system (Fig. 1) can take into account the loss of strength and stiffness caused by dehydration and crack propagation during heating, the rapid increase in internal temperature and loss of bond strength between reinforcement steel and concrete due to the spalling of the cover concrete, and the strength recovery due to post-fire re-curing (Iwama et al. 2018, 2019, 2020, 2021).

Thus far, the authors have carried repeated upgrade and verification of the multi-scale platform (Ishida and Maekawa 1999; Maekawa et al. 2003, 2008) with a primary focus on material and structural behavior at high temperatures. The purpose of this study is to verify the accuracy and applicability of the upgraded multi-scale platform (Iwama et al. 2018, 2019, 2020, 2021) shown in Fig. 1, focusing on the behavior and remaining shear capacity after high temperature heating. The main points of interest here regarding structural members are 1) the process of recovery (rehydration) of the concrete pore structure at room temperature after denaturation by high temperature exposure, 2) the compression characteristics of concrete that has been exposed to high temperatures, and 3) the model of tensile strength and fracture energy. Thus, from the viewpoint of 1) (existing rehydration model), we conducted a verification experiment simulating the moisture absorption process of concrete after exposure to high temperature. Furthermore, from the viewpoints of 1) and 2), the load bearing capacity of RC beams with a small shear span
ratio, in which the compression arch mechanism is prominent, was targeted for verification. Additionally, from viewpoints 1) and 3), RC beams with a large shear span ratio, which exhibit the brittle shear failure mode, were selected for verification.

2. Experiment of high strength RC beams subjected to high temperature heating

The shear capacity of RC members with cracks introduced by reinforcing bar corrosion or ASR (alkali-silica reaction) may be greater than that of sound members (Okada et al. 1988; Toongoenthong and Maekawa 2004; Tatsuki et al. 2007). This is mainly due to the development of the tied arch effect caused by the reduction of the bond between concrete and main reinforcement. When RC beams are subjected to high temperatures, the difference between the thermal expansion rates of the concrete and reinforcing bars causes cracks along the reinforcing bars in the high temperature region. Further, loss of bond strength is caused by loss of cover due to spalling. Accordingly, the same effects as those of rebar corrosion and ASR might be realized in the case of fire-exposed members as well.

On the other hand, rapid drying of concrete at high temperature and strength loss and spalling of hardened cement paste due to loss of crystallized water, as well as decrease in shear capacity owing to heat damage of the web resisting the shear force, are also predicted. Multiple conflicting factors affect load-bearing capacity. Therefore, shear failure of RC beams is considered to be useful for the comprehensive verification of analytical models. In this section, we examine the changes in shear capacity and failure mode caused by exposure to high temperature using shear failure precedence type beam members without shear reinforcement.

2.1 Outline of experimental specimens

Three values for shear span to depth ratio a/d, 1.2, 2.2 and 3.2, were used. The experimental specimen dimensions and the main reinforcement ratio were set to ensure shear failure (Fig. 2). The concrete cover thickness was 50 mm. The main reinforcement was bent through an angle of 90° or 180° to secure sufficient anchorage length. High-strength concrete with high risk of spalling was used (Table 1). Investigating the difference in damage due to spalling during high temperature heating, two types of cross sections (Case 1 and Case 2) were prepared for a/d = 1.2 (Fig. 2).

The a/d = 1.2 specimens were demolded the day after casting and subjected to sealed curing until the age of 7 days. The heating test specimens underwent air curing until the age of 33 days in the laboratory, and then were subjected to the heating test. After the heating test, the specimens underwent air curing for 7 days in the laboratory, and where then subjected to the loading test. The non-heating test specimens underwent air curing in the same laboratory until the age of 40 days, and then were subjected to the loading test. In both cases, the number of days from casting to the loading test was 40 days.

![Fig. 1 Outline of multi-scale modeling of structural concrete (including upgrade for high temperature).](image-url)
The \(a/d = 2.2\) and \(a/d = 3.2\) specimens were demolded the day after casting and wet cured using a curing mat until the age of 63 days. Drying was prevented by sprinkling water on the curing mat as needed. The \(a/d = 2.2\) specimens underwent air curing until 105 days of age, and the \(a/d = 3.2\) specimens underwent air cured until 91 days of age, and then the specimens were heated in a large furnace. After the heating test, the specimens underwent air curing for 21 days in the laboratory, after which they were subjected to the loading test. Both the \(a/d = 2.2\) and \(a/d = 3.2\) non-heating test specimens were wet cured until the age of 63 days. The \(a/d = 2.2\) specimens underwent air curing until the age of 126 days, and the \(a/d = 3.2\) specimens underwent air curing until the age of 112 days. The number of days from casting to the loading test was the same for both the heating test specimens and the non-heating test specimens.

### 2.2 Heating test

The beams were subjected to a high temperature history using a large heating test furnace. Heating was performed for 2 hours according to the standard heating program specified in ISO 834 (ISO 834 control in Fig. 3). After heating, the furnace was allowed to cool naturally for one day with the door closed. The specimen setup is shown on the middle in Fig. 3. As shown in this figure, the temperature during heating was measured by thermocouples on the upper, lower, and side surfaces of the specimens. Were the part corresponding to the bearing area to explode, this could interfere with the loading test, so this area was protected with insulating material. The measurement and thermal analysis results of the temperature inside the RC beam during heating test in Case 2 with \(a/d = 1.2\) are shown on the right side of Fig. 3. The surface of the members was exposed to a high temperature of approximately 1000°C in the furnace.

### Table 1 Mix proportion of concrete.

| G (max.) (mm) | W/C (%) | s/a (%) | Unit weight (kg/m³) |
|---------------|---------|---------|---------------------|
| 20 | 25 | 43.5 | 175 | 700 | 644 | 849 | 11.9 |

W: water, C: cement, S: fine aggregate, G: coarse aggregate, SP: super plasticizer, s/a: fine aggregate ratio

*1River sand, surface-dry density = 2.58 g/cm³, rate of water absorption = 2.21%.
*2River gravel, surface-dry density = 2.65 g/cm³, rate of water absorption = 0.53%.

![Fig. 2 Dimensions of specimens.](image)

![Fig. 3 Outline of heating test.](image)
and the central part of the beam may reach a high temperature of about 400°C.

The temperatures around the specimens were lower than the average temperature of the heating furnace. The specimens were set up so that they would not be exposed directly to the flames from the burner, and measures were taken to minimize uneven heating around the specimens in view of the fact that convection of hot air near the front of the burner in the furnace promoted uneven heating.

2.3 Loading test
After slow cooling, the specimens were subjected to shear loading by three-point bending using two simple supports and a load applied at the center of the beam (Fig. 4). Friction at the bottom surface of the supports was removed to eliminate constrained axial force generated in the specimen. The loading speed was set to about 1 kN/sec so as to prevent the influence of inertial force. Preloading was done with plaster placed between the specimen and the supports to ensure levelness of the specimen. The preload amount was about 10% of the maximum load bearing capacity.

Displacement was measured using the immovable beam shown in the photo on the left in Fig. 4. To exclude rigid-body displacement of the beam, the amount of deflection at the loading point was obtained by the relative vertical displacement, calculated as the difference between the vertical displacement just below the loading point and the vertical displacement just above the supports. Horizontal displacement of the loading point and supports was also measured to verify the simple support conditions. The load was applied while monitoring the movement of the supports based on the relative horizontal displacement, calculated as the difference between the horizontal displacement of the loading point and the horizontal displacement of the supports. Cylindrical specimens were prepared for the compression test at the time of specimen fabrication. The a/d = 1.2 specimens underwent sealed curing for 40 days, and the a/d = 2.2 and a/d = 3.2 specimens underwent water curing for 112 days. The compressive strength of the a/d = 1.2 specimens was 98.4 MPa, and that of the a/d = 2.2 and a/d = 3.2 specimens was 92.6 MPa.

2.4 Experimental results of heating test
Figure 5 shows the damage of the specimens after the heating test. For a/d = 1.2, it can be seen that area of loss due to spalling is larger in Case 2 with larger beam thickness than in Case 1 with smaller beam thickness. This is considered to be linked to the fact that the specific surface area of Case 2 is smaller than that of Case 1 (Fig. 2). In Case 2, which has a small specific surface area, the temperature difference between the vicinity of the heated surface and the inside is larger, which is less conducive to the release of water vapor to the outside. The a/d = 2.2 and a/d = 3.2 specimens showed the same type of damage as the a/d = 1.2 specimen, as previously reported (Higuchi et al. 2020). For the specimens for which spalling could not be prevented despite protection of the supports, the supports were reinforced with mortar to ensure levelness of the specimen during loading. Strictly speaking, concrete age and curing conditions in each case were slightly different since the conditions of the heating furnace and curing locations of specimens were not exactly the same. Thus, the thermo-mechanistic states at the time of the heating tests were variable, but those were kept within the narrow band of deviation.

2.5 Experimental results of loading test
Figure 6 shows the surface condition of the specimens after the loading test. As determined by visual inspection, the failure mode of the non-heating test specimens was shear compression failure in the case of a/d = 1.2 and a/d = 2.2 (Figs. 6B, 6D and 6I), and diagonal tension failure in the case of a/d = 3.2 (Fig. 6J). After the occurrence of diagonal cracks, the load bearing capacity dropped sharply.

On the other hand, in the case of heating test specimens, cracks dispersed even after diagonal cracking occurred (Figs. 6A, 6C and 6H), and the load-bearing capacity did not decrease as rapidly as in the case of the non-heating test specimens. At around the maximum load, the concrete cover spalled (Fig. 6E). It is inferred that the bond between concrete and main reinforcement was degraded by the heating. The web of the a/d = 3.2 specimens showed areas where concrete was lost due to spalling (Fig. 6F). Diagonal cracks developed along the

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**Fig. 4** Installation status of measuring equipment and test specimens.
sides of these damaged areas. Damage to fixing parts (Fig. 6G) was also confirmed.

The RC members subjected to fire developed many cracks, but as the result of crack dispersion, the failure mode changed to ductile failure. Figure 7 shows the load-vertical displacement relationships of the various specimens obtained in this experiment. The ratio of maximum load-bearing capacity of the heating test specimens to that of the non-heating test specimens (remaining load-bearing capacity ratio) was 0.39 for the Case 1 of a/d = 1.2, 0.57 for Case 2 of a/d = 1.2, 0.61 for a/d = 2.2, and 0.47 for a/d = 3.2. Although the stiff-
ness of the member is reduced to about 1/3 to 1/4, the high-strength concrete RC beam, which may exhibit somewhat brittle nature at a room temperature, shows rather ductile fracture mode after high temperature heating.

Comparing three cases with equal member thickness, a/d = 1.2_Case-1, a/d = 2.2 and a/d = 3.2, the remaining load-bearing capacity ratio is a/d = 1.2_Case-1 < a/d = 3.2 < a/d = 2.2. In the case of the slender members with a/d = 2.2 and a/d = 3.2, the bond between the concrete and the main reinforcement deteriorated due to heating, and the tied-arch load-bearing mechanism probably developed. This has the effect of increasing shear capacity.

On the other hand, the a/d = 1.2 members (deep beams) showed the tied-arch load-bearing mechanism from the beginning. Therefore, it is known that concrete compressive strength directly affects a member’s load-bearing capacity. The a/d = 1.2 specimens, which showed a large decrease in load-bearing capacity, are considered to be the result of strong effect of high temperature heating on compressive strength.

Comparing Case 1 and Case 2 with a/d = 1.2, the remaining load-bearing capacity ratio is greater for Case 2. Since in Case 2 the members have a large cross section, the temperature at the center is lower than in Case 1. The volume of concrete that maintained its strength was large overall. The impact of the loss of web due to spalling was also relatively small.

The tied-arch effect may get predominant owing to the reduced bond between concrete and main reinforcing bars caused by high temperature heating, and that the shear capacity of the RC beam is consequently increased. On the one hand, the strength of the hardened cement paste might be reduced, and concrete of the web that resists against the shear force is damaged by cracks and spalling. This is the negative impact to the shear capacity. These positive and negative effects are thought to be greatly reflected in the experimental results of the RC beams as well.

### 3. Properties of rehydration of CaO at post-fire-curing

When concrete is subjected to high temperature heating of 400°C or above, water dissociates from the hardened crystals and Portlandite \([\text{Ca(OH)}_2]\) changes to quicklime \((\text{CaO})\) (Vance et al. 2015). During the moist air-curing period after heating and slow cooling, the quicklime rehydrates and returns to Portlandite (Poon et al. 2001; Alonso and Fernandez 2004; Park et al. 2015). The original models (Iwama et al., 2018, 2019, 2020) incorporate also a dehydration-rehydration model that takes into account strength loss due to high temperature heating and strength recovery due to rehydration. Here, strength recovery is obtained by analysis of the densification of the pore structure by the return of the quicklime to the Portlandite prior to loss of crystallized water. Since the presence of rehydration reactant in the crack spaces is not taken into account, the recovery of tensile strength of concrete and volume expansion due to rehydration are not reflected in the analysis, for evaluation leaning toward the safe side. On the other hand, recent studies have reported recovery of tensile strength by recuring (Li et al. 2020) and volume expansion due to rehydration (Suh et al. 2020). This section describes the creation of a trial model aiming at the sophistication of the rehydration model, and verification of that model based on the behavior of RC members after heating.

#### 3.1 Outline of experiment

After high temperature heating, the volume change and compressive strength of cylindrical specimens re-cured in a moist air environment were measured. In addition, the crystals after rehydration were examined by scanning electron microscope (SEM). An experiment directly supplying liquid water to quicklime on its own was also conducted.

Table 2 lists the mix proportion of the test specimens used in the material test. As in the high-strength RC beams, the dosage of water was kept constant at 1.2% while the contents of fine aggregate and super plasticizer were varied in a range of 242% to 968% and 1162% to 14.5%.

| W/C (%) | s/c | Unit weight (kg/m³) |
|---------|-----|---------------------|
| 25      | 1.2 | 242                 |
|         |     | C 968               |
|         |     | S 1162              |
|         |     | SP 14.5             |

Table 2 Mix proportion of mortar specimens.

W: water, C: cement, S: fine aggregate, SP: super plasticizer, s/c: fine aggregate to cement ratio
*1River sand, surface-dry density = 2.58 g/cm³, rate of water absorption = 2.21%.

![Fig. 7 Load-displacement relationship of each specimen at the center of the span.](image)
beams discussed in Section 2, the water-cement ratio was 25%. The presence of coarse aggregate may form a weak layer on the aggregate surface, and/or fine cracks may occur due to the differential thermal expansion of mortar and the coarse aggregate during heating. So as to minimize these effects, mortar specimens were targeted for the verification of the proposed model. A total of six cases were set as follows: before heating (before fire), immediately after heating (after fire), and after re-curing (RH-30% curing, RH-60% curing, RH-90% curing and water curing). The average value of three specimens in each case was used as the measured value.

The mortar specimens were demolded the day after casting, and they were then sealed and cured in a temperature-controlled room at 20°C until the age of 28 days. After the sealed curing, the compressive strength was measured in the case before fire. For the other cases, heating was done using an electric furnace. In this experiment, the temperature was raised to 1000°C at the heating rate of 2.0°C/min to prevent damage by spalling, and after holding the temperature at 1000°C for one hour, the temperature was lowered at the rate of 2.0°C/min. The temperature was measured by the thermocouple mounted on the electric furnace, and the temperature rise/fall speeds were controlled in reference to the measurement of the structural test. The maximum temperature was set to 1000°C according to the maximum temperature of the heating test of RC beams.

The length change of the specimens was measured every day from immediately after heating (just after the temperature in the furnace dropped to room temperature) until 7 days of re-curing. The measurements were continued until the 14th and 21st day of re-curing. The length change in the height direction was measured at three points using calipers, and the three measurement values were averaged to obtain the average length change of the specimen.

### 3.2 Comparison of compressive strength after post-fire-curing in various RH

The average values of the compressive strength test are shown in Fig. 8. The compressive strength immediately before heating was 105.6 MPa, the compressive strength immediately after heating was 14.5 MPa and the remaining strength ratio was 13.7%. In the case of re-curing at RH = 30%, compressive strength was 11.1 MPa; in the case of re-curing at RH = 60%, it was 14.9 MPa; at RH = 90%, it was 14.0 MPa; and in the case of re-curing in water, it was 23.1 MPa. The right side of Fig. 8 shows the compressive strength just after heating and after re-curing for each of the three specimens. Based on the results, it can be said that the scatter in strength in this experiment is about ±2 MPa.

Compressive strength was almost the same at RH = 60% (ordinary air curing) and RH = 90%, but compressive strength recovered significantly in the case of re-curing in water. This is consistent with previous findings (Park et al. 2015; Suh et al. 2020). On the other hand, re-curing at RH = 30% resulted in a slight decrease in strength. Further, there are reports that re-curing in air may also reduce strength (Park et al. 2015; Suh et al. 2020). These results suggest that the rehydration of quicklime (CaO) comes with both positive and negative effects.

The reaction of quicklime is generally exothermic and proceeds rapidly, producing Portlandite. As this fills the voids in the hardened material that have become sparse due to heating, restoration of strength and stiffness can be expected. However, it is unlikely that all of that regeneration (Akca and Özyurt 2020; Ming et al.)

### Table 4

| Case name                | No.1  | No.2  | No.3  |
|--------------------------|-------|-------|-------|
| After-fire               | 14.69 | 14.18 | 14.67 |
| RH-30%-curing            | 11.44 | 10.80 | 10.92 |
| RH-60%-curing            | 14.01 | 15.72 | 14.86 |
| RH-90%-curing            | 14.71 | 12.41 | 14.92 |
| Water-curing             | 22.32 | 23.80 | 23.06 |

Fig. 8 Compressive strength of each case (before fire, after fire and after post-fire-curing).
2020) will occur in the original gel pores. This is because Portlandite occurs as large hexagonal plates. Figure 9 shows electron micrographs of mortar specimens after re-curing. In fact, Portlandite, which is produced by the rehydration of quicklime, was observed to precipitate in pores with pore size of 100 μm or more.

3.3 Expansion of mortar specimen due to rehydration of calcium oxide

Figure 10 shows the length change of the specimen during the re-curing period, based on the height of the specimen immediately after heating. At the end of 21 days of re-curing, the height change was 1.05 mm for the case re-cured at RH = 30%, 0.73 mm for the case re-cured at RH = 60%, and 0.77 mm for the case re-cured at RH = 90%. The height change for the case that was re-cured under water was 0.40 mm. The smaller the amount of expansion, the greater the strength after re-curing. The expansion of the concrete during the curing period is attributed to the approximate doubling in volume that takes place when quicklime changes to Portlandite (Yasue and Arai 1995; Chikazawa and Fuji 2001). Based on the fact that the pH of the curing water increased during water curing, concrete expansion is considered to have been suppressed by elution of soluble Portlandite.

Figure 11 shows the results of an experiment using quicklime (CaO) alone. When liquid water is added to quicklime, the quicklime rapidly expands and heat is generated. When the amount of water supplied is small, the quicklime expands while destroying its own skeleton (Miyatani 2004), taking on an almost powdery consistency. However, it has been reported that when the amount of water supplied is large, the heat generation is suppressed by the cooling effect of the water itself, and a thin layer of calcium hydroxide is formed on the surface layer of calcium oxide (Yasue and Arai 1995). It has been reported that after the formation of this layer, the ingress of water becomes diffusion limiting, resulting in a slow hydration reaction (Yasue and Arai 1995). These effects were also shown in this experiment. Actually, the expansion of mortar was large at RH = 30%, where the moisture could be less supplied (see Fig. 10). On the contrary, the expansion was suppressed at RH = 60% and RH = 90% and resulted in the minimum under condensed water similarly to the case of Fig. 11.

It is surmised that if sufficient water is retained in the hardened cement paste, some of the Portlandite formed by rehydration dissolves in the water and this reduces expansion. In addition, when calcium hydroxide is produced, it is considered that the expansion becomes large when the amount of water in the hardened cement is small. From the above, a mechanical model was set up in which quicklime is transformed by water into Port-
landite with a large-scale crystalline structure and expands, causing fine cracks in the hardened cement paste (Suh et al. 2020), and resulting in a decrease in concrete strength, as discussed later. At the structural member level, vapor in the air is absorbed during re-curing, and quicklime in the hardened cement is rehydrated, leading to expansion of the concrete composite. When this expansion is restrained by reinforcing bars, prestress is introduced to concrete. In the multi-scale analysis (Ishida and Maekawa 1999; Maekawa et al. 2003, 2008), this self-equilibrated event is automatically reproduced and associated with the structural performance evaluation.

### 3.4 Development of adhesive strength due to calcium oxide supplied water

It has been reported that crack width can be reduced by supplying moisture to the RC beam specimens after heating (Suh et al. 2020). There is a possibility that cracks caused by high temperature heating can be repaired during the re-curing period. In this section, we examined the adhesive characteristics that develop when water is supplied to quicklime. Quicklime powder was applied to the split face of a fractured mortar specimen (50 mm × 100 mm). Assuming cracks in the structure, the specimen was bound with rubber bands to prevent separation and fall-off (Fig. 12). After 24 hours, the rubber band restraint was removed and the specimen was supported so that the split face was parallel to the floor. Although full self-recovery of tensile strength was not achieved, it was confirmed that the adhesive strength was sufficient for the specimen to resist its own weight. When calcium hydroxide is generated by rehydration of quicklime during re-curing after high temperature heating, it is considered that if Portlandite precipitates in the cracked space, it will affect the tensile properties of the cracked concrete.

### 4. Upgrade of rehydration model at post-fire-curing

Existing models of quicklime rehydration (Iwama et al. 2018, 2019, 2020) assume that Portlandite precipitates again in the space lost by dehydration of Portlandite (converted to quicklime) (Fig. 13, previous model). Self-recovery of tensile strength properties is not reflected in the mechanical model because it does not allow the precipitation of crystals in large crack spaces. However, based on the fact that re-precipitation of Portlandite in large pores has been observed, Portlandite precipitation can be assumed to have some influence on tensile characteristics if it occurs also in crack spaces.

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Fig. 12 Adhesive strength caused by rehydration of calcium oxide.

Fig. 13 Outline of proposed rehydration model of calcium oxide.
The following trial model was developed, wherein, a) Portlandite, which is produced by the rehydration of quicklime, causes the expansion of the hardened cement paste by forming outside the original gel pores, and b) Portlandite precipitates within cracks, affecting tension-softening properties. Using this model, it was decided to examine the sensitivity of member response (Fig. 13).

4.1 Modeling of expansion due to production of Ca(OH)\(_2\)

Based on the aforementioned experimental results and previous findings (Akca and Özyurt 2020; Ming et al. 2020; Suh et al. 2020), a dynamic model for the conversion of quick lime to Portlandite was established as follows.

\[
E_{CH} = E_{CH} \cdot \int \frac{(W_{CH})}{\rho_{CH}} dt
\]

(1)

where \(V_{rCH}\) is the apparent volume of Portlandite causing volume expansion (m\(^3\)/m\(^2\)), \(W_{CH}\) is the weight generated per unit time by rehydration (kg/m\(^3\)), \(\rho_{CH}\) is the unit weight of Portlandite (kg/m\(^3\)), \(E_{CH}\) is a function that defines the ratio of volume expansion to the actual volume of Portlandite, \(a\) is the coefficient that defines the maximum expansion ratio (tentatively 8.0 in the proposed model), and \(RH_{pore}\) is the intrapore humidity of the hardened cement paste.

Since the hexagonal plate-like crystals of Portlandite are thin and large, rehydration is considered to cause expansion larger than the actual volume. In the proposed model, this effect is represented by \(E_{CH}\). From the experimental findings, it was assumed that the ratio of expansion relative to actual volume depends on the humidity inside the pores, and that volume expansion almost never occurs when there is sufficient free water. Further, when crystal growth caused by Portlandite generated by rehydration is hindered by the solid part of the concrete, the expansion force acts on the skeleton of the hardened cement paste Eqs. [(1) and (2)]. This property is expressed below with reference to a two-phase model of hardened cement paste and aggregate (Asamoto et al. 2006; Maekawa et al. 2003, 2008).

\[
\sigma_t = V_{ag} \sigma_{ag} + (V_{ap} + V_{rCH}) \sigma_{ap}
\]

(3)

where \(\sigma_t\) is the tensile stress of concrete (MPa), \(\sigma_{ap}\) is the aggregate stress (MPa), \(V_{ag}\) is the aggregate volume (m\(^3\)), \(\sigma_{ag}\) is the hardened cement paste stress (MPa), \(V_{ap}\) is the hardened cement paste volume (m\(^3\)), and \(V_{rCH}\) is the apparent volume of calcium hydroxide that causes volume expansion (m\(^3\)/m\(^2\)).

This model reproduces the event where the hardened cement paste expands in volume due to the formation of calcium hydroxide during re-curing, and in some cases destroys itself and loses strength.

4.2 Modeling of increase of bond properties due to rehydration of CaO

Portlandite produced by quicklime rehydration may help self-repair of cracks (Section 3.4). In this section, we attempt to back-calculate the extent of this effect from sensitivity analysis of the structural response. In the multi-scale analysis, strain softening of concrete after cracking is expressed as follows (Maekawa et al. 2003).

\[
\sigma_t = f_t \left( \frac{\varepsilon_{cr}}{\varepsilon_t} \right) + \alpha \cdot f_t \left( \frac{\alpha \cdot \varepsilon_{cr}}{\varepsilon_t} \right)^{0.4}
\]

(4)

where \(\sigma_t\) is the tensile stress of concrete (MPa), \(f_t\) is the tensile strength of concrete (MPa), \(\varepsilon_{cr}\) is the concrete cracking strain, \(\varepsilon_t\) is the tensile strain, and \(c\) is the tension softening coefficient and indicates the bond properties. It is assumed that the Portlandite generated by the rehydration of quicklime bears a part of the tensile stress acting on the concrete. The amount of Portlandite contributed for tension softening is expressed as follows, and the sensitivity of the structural response will be examined in a later section.

\[
\sigma_t = f_t \left( \frac{\varepsilon_{cr}}{\varepsilon_t} \right) + \alpha \cdot f_t \left( \frac{\alpha \cdot \varepsilon_{cr}}{\varepsilon_t} \right)^{0.4}
\]

(5)

where \(\alpha\) is a coefficient that defines the ratio of tensile stress after cracking borne by the Portlandite precipitated by hydration. From the results of the sensitivity analysis described later, it was deductively estimated to be 0.15 (portion corresponding to self-repair by rehydration). It was confirmed that even a small ratio has some effect on the load bearing behavior of mortar specimens and RC beam members (see below). From the perspective of fracture mechanics, it has also been confirmed that the influence of self-healing decreases as the size of the member increases (Maekawa et al. 2003). The effect of member size on shear failure of members that have a high temperature history will be left for future verification.

During and after heating, calcium oxide and calcium hydroxide react with CO\(_2\) gas in the air to produce Calcite (CaCO\(_3\)). In the model proposed in this study, based on the experimental results in Section 3, it is assumed that only Portlandite produced by rehydration of quicklime contributes to the expansion and tensile properties mentioned above. Strength recovery by carbonation is not being considered at this time for safety reasons. We expect that further refinement of models related to carbonation will lead to a more accurate understanding of strength properties.

5. Experimental validation

In this section, the modified model discussed in Section 4 is validated by structural testing. The expansion and compressive strength of the specimens after re-curing in different humidity environments, and the shear capacity
and deformation behavior of RC beams after heating will be discussed. The RC beam after the heating experiment had an explosive spalling of concrete cover. The multi-scale analysis (Iwama et al. 2018, 2019, 2020) takes into account this event as mechanical damages. In particular, the spalled-off elements are computationally replaced with the equivalent boundary transfer elements to link the ambient states. Then, the inside element behind the spalled-off is computationally exposed to the fire consequently. When the crack strain of spalled-off elements is so large (1%) as to bear almost zero stresses in compression and tension, these elements are mechanically killed and removed.

5.1 Validation of expansion behavior and compressive strength in post-fire-curing
The length changes of concrete specimens cured under different humidity conditions were analyzed and verified by comparison with the experiment. As in the experiment, sealed curing was conducted at 20°C until 28 days of age. After the initial curing, the temperature was raised to 1000°C at the heating rate of 2.0°C/min, and after holding the temperature at 1000°C for one hour, the temperature was lowered at the rate of 2.0°C/min. After the temperature of the specimens was lowered to the laboratory’s room temperature, they were subjected to a humid environment (RH = 30%, 60%, 90% and water) and re-cured for 21 days. The change in length of the specimens during this re-curing period was measured using the height of the specimens after heating as reference.

The results of the original model (Iwama et al. 2018, 2019, 2020) and the trial one of this study are shown in Fig. 14 (original model: RH-30%_B, RH-60%_B, RH-90%_B, Water_B and the trial model: RH-30%_S, RH-60%_S, RH-90%_S, Water_S). The changes in length after 21 days roughly capture the trend of the experimental results. However, the analytical expansion amount at 1 day of re-curing is smaller than that of the experiment in all cases. This may be due to the analytical water absorption amount being less than in the experiment. In the proposed model, it is considered that the pore structure of the hardened cement paste becomes sparse due to high temperature heating, and that the water vapor and liquid water migration resistance decreases due to the occurrence of cracks (Bazant et al. 1987; Ishida and Maekawa 1999; Maekawa et al. 2008).

As shown in Fig. 14, as moisture gradually permeates into the hardened cement paste, the expansion behavior is well reproduced in the analysis.

Compared with the original model, substantial progress in evaluating the structural concrete performances after high temperature heating is obtained although there are still issues to be upgraded in future. The effects of carbonation during and after high temperature heating will be focused on.

Figures 15 and 16 show the analytical values for compressive strength of the original model and the trial one, which is an integrated mechanical model of both expansion and tensile stress bearing by Portlandite caused by quicklime rehydration before and after heating and after 21 days of re-curing in a moist air environment. Although the original model was able to roughly approximate the experimental results, the trial model was able to predict the experiment quantitatively and with good accuracy. In particular, it captures the phenomenon of the compressive strength after re-curing at RH = 30% being less than the compressive strength...
immediately after heating. This is a result of the effect of structural failure due to volume expansion during re-curing in a low-humidity environment outweighing the effect of strength increase due to rehydration.

5.2 Validation of shear capacity and deformation of high strength RC beams

Element models of RC beams to be subjected to heating are shown in Fig. 17. To capture the steep temperature and humidity gradient caused by rapid high temperature heating and moisture dissipation, the element size of the surface layer of the beam was in the order of a few millimeters. For the mass transfer model when using elements smaller than coarse aggregate, refer to the existing literature (Gebreyouhannes et al. 2014; Yoneda et al. 2015). Elastic elements were placed on the loading plate and supports. Regarding the curing conditions of the specimens, the temperature measured by the heating test described in Section 2.2 was set.

The analysis results of the original model and trial model are shown in Figs. 18 and 19. Widely dispersed diagonal cracks are reproduced in both heating test specimens. It is also largely possible to reproduce the damage to the fixing parts. In the non-heating test specimens, localized diagonal cracks were observed in the experiment, and the failure mode was similar in the analysis.

The shear capacity before and after heating was also well evaluated by both models, but for a/d = 3.2, shear capacity was overestimated. On the other hand, the stiffness of the member in the original model was underestimated for the deep beam of a/d = 1.2, where the strong compressive strut appears. The trial model shows an improvement in the evaluation of stiffness of rather slender beams of a/d = 1.2, 2.2 and 3.2. We have no difference between the trial and the original models in terms of the load-bearing capacity. From this investigation, the rehydration model of quicklime introduced in this study has the impact of increasing the member stiffness, especially in case of the deep beams. The trial model was confirmed to bring about some improvement for member stiffness. The authors will further deepen this discussion in future.

Fig. 15 Validation of compressive strength after post-fire-curing: Original referential model.

Fig. 16 Validation of compressive strength after post-fire-curing: Trial model.
Fig. 17 Outline of numerical models of each high strength RC beam.

Fig. 18 Computed shear capacity and failure mode: Original referential model.

Fig. 19 Computed shear capacity and failure mode: Trial model.
6. Conclusions

The following is a summary of the findings of this study.

1. After high temperature heating of RC beams leading to brittle fracture followed by slow cooling, the application of shear force did not lead to sudden failure even after the occurrence of diagonal cracks, and along with crack dispersion, the beams eventually ended in ductile failure. Ductility of the heated RC beam specimens was about 3 to 4 times that of the unheated ones.

2. The shear capacity of the RC beams heated to high temperature decreased, remarkably so in the deep beam with a/d = 1.2. For the a/d = 2.2 and a/d = 3.2 specimens, the rate of decrease in load-bearing capacity was smaller than in the deep beam due to the development of the tied-arch mechanism that accompanied degradation of the bond between the concrete and the main reinforcement.

3. In RC beams with a large member cross section, spalling of the web surface was remarkable, but temperature rise at the center of the member was suppressed to a relatively low level, and the decrease in shear strength was suppressed.

4. The rehydration of quicklime (CaO) produced by high temperature heating resulted in the precipitation of Portlandite [Ca(OH)₂] in coarse pore about 100 μm in size. This was confirmed by SEM analysis during the water curing period after slow cooling.

5. During the curing period after slow cooling, quicklime reacted by absorbing water vapor in the air, and the concrete specimens expanded. Volume expansion is attributed to the formation of Portlandite. When the water supply was excessive, the expansion of concrete was inhibited by the dissolution of Portlandite.

6. A simple method to describe the behavior of Portlandite generated by rehydration of quicklime in coarse pores after slow cooling in multi-scale analysis was proposed. Compared with the original model, the new model allows better estimation of the expansion of concrete specimens and recovery of compressive strength in the slow cooling period after high temperature heating.

7. The remaining shear capacity and failure mode of high-strength RC beams placed at room temperature after heating could be roughly estimated. However, in the case of elongated shear failure precedence type members, prediction accuracy of remaining member stiffness after heating is high, but remaining load-bearing capacity is estimated on the high side. Moreover, although residual ultimate strength can be evaluated accurately for deep beams, member stiffness tends to be calculated on the low side.

8. From the above validation, the functionality of the proposed model as a platform for multi-scale analysis was confirmed, but its quantitative accuracy needs to be improved. The effect of carbonation is considered by using the model verified at room temperature. The applicability of the model at high temperatures will be investigated in the future.

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References

Akca, A. T. and Özyurt, N., (2020). “Post-fire mechanical behavior and recovery of structural reinforced concrete beams.” Construction and Building Materials, 253, Article ID 119188.

Alonso, C. and Fernandez, L., (2004). “Dehydration and rehydration processes of cement paste exposed to high temperature environments.” Journal of Materials Science, 39(9), 3015-3024.

Asamoto, S., Ishida, T. and Maekawa, K., (2006). “Time-dependent constitutive model of solidifying concrete based on thermodynamic state of moisture in fine pores.” Journal of Advanced Concrete Technology, 4(2), 301-323.

Chikazawa, M. and Fuji, M., (2001). “Nano particles of lime and calcium carbonate.” Journal of the Society of Inorganic Materials, Japan, 8, 507-514. (in Japanese)

Dwaikat, M. B. and Kodur, V. K. R., (2009). “Response of restrained concrete beams under design fire exposure.” Journal of Structural Engineering, 135(11), 1408-1417.

Gawin, D., Pesavento, F. and Schrefler, B. A., (2006). “Towards prediction of the thermal spalling risk through a multi-phase porous media model of concrete.” Computer Methods in Applied Mechanics and Engineering, 195(41-43), 5707-5729.

Gawin, D., Pesavento, F. and Castells, A. G., (2019). “On reliable predicting risk and nature of thermal spalling in heated concrete.” Archives of Civil and Mechanical Engineering, 18(4), 1219-1227.

Gebreyouhannes, E., Yoneda, T., Ishida, T. and Maekawa, K., (2014). “Multi-scale based simulation of shear critical reinforced concrete beams subjected to drying.” Journal of Advanced Concrete Technology, 12(10), 363-377.

Hashim, A. M. and Kadhum, M. M., (2021). “Numerical and experimental study of postfire behavior of concentrically loaded SIFCON columns.” ACI Structural Journal, 118(1), 73-86.

Hedden, J., Quagliata, M. and Wandzilak, T., (2010). “Emergency renovation, steel bridge news.” In: Modern Steel Construction. Chicago, USA: American Institute of Steel Construction, 36-39.

Higuchi, K., Iwama, K. and Maekawa, K., (2020). “Shear capacity of high strength RC beams subjected to high temperature heating.” In: Proc. 3rd International Conference on Civil, Architectural and Environmental
Engineering, Christchurch, New Zealand 23-25 November 2020.

Hoj, N. P. and Tait, C., (1999). “Great Belt tunnel repairs and refurbishment.” Tunnel Management International, 9, 16-22.

Ishida, T. and Maekawa, K., (1999). “An integrated computational system of mass/energy generation, transport and mechanics of materials and structures.” Doboku Gakkai Ronbunshu, 627(44), 13-25. (in Japanese)

Iwama, K., Ishibashi, N. and Maekawa, K., (2018). “Modeling of decomposition and self-healing processes of hardened cement paste exposed to high temperature.” In: Proc. 8th International Conference of Asian Concrete Federation, Fuzhou, China 4-7 November 2018. Pathumthani, Thailand: Asian Concrete Federation, 227-234.

Iwama, K., Higuchi, K. and Maekawa, K., (2019). “Multi-scale modeling of deteriorating concrete at elevated temperature and collapse simulation of underground ducts.” In: G. Pijaudier-Cabot, P. Grassl and C. La Borderie, Eds. 10th International Conference on Fracture Mechanics of Concrete and Concrete Structures, Bayonne, France 23-26 June 2019. Illinois, USA: International Association for Fracture Mechanics of Concrete and Concrete Structures, Article ID 235478.

Iwama, K., Higuchi, K. and Maekawa, K., (2020). “Model-based assessment of long-term serviceability and fire resistance for underground reinforced concrete ducts.” Structural Engineering International, 30(4), 506-514.

Iwama, K., Higuchi, K. and Maekawa, K., (2020). “Thermo-mechanistic multi-scale modeling of structural concrete at high temperature.” Journal of Advanced Concrete Technology, 18(5), 272-293.

Iwama, K., Kato, Y., Baba, S., Higuchi, K. and Maekawa, K., (2021). “Accelerated moisture transport through local weakness of high-strength concrete exposed to high temperature.” Journal of Advanced Concrete Technology, 19(2), 106-117.

JCI, (2017). “Evaluation of concrete performance under high temperature environment” (Research Committee Report JCI-TC154A). Tokyo: Japan Concrete Institute. (in Japanese)

Kalifa, P., Menneteau, F. D. and Quenard, D., (2000). “Spalling and pore pressure in HPC at high temperatures.” Cement and Concrete Research, 30(12), 1915-1927.

Kalifa, P., Chéné, G. and Gallé, C., (2001). “High-temperature behavior of HPC with polypropylene fibres: From spalling to microstructure.” Cement and Concrete Research, 31(10), 1487-1499.

Kodur, V. and Megrath, R., (2003). “Fire endurance of high strength concrete columns.” Fire Technology, 39, 73-87.

Kodur, V. K. R. and Agrawal, A., (2016). “An approach for evaluating residual capacity of reinforced concrete beams exposed to fire.” Engineering Structures, 110, 293-306.

Li, L., Shi, L., Wang, Q., Liu, Y., Dong, J., Zhang, H. and Zhang, G., (2020). “A review on the recovery of fire-damaged concrete with post-fire-curing.” Construction and Building Materials, 237, Article ID 117564.

Maekawa, K., Ishida, T. and Kishi, T., (2003). “Multi-scale modeling of concrete performance - Integrated material and structural mechanics.” Journal of Advanced Concrete Technology, 1(2), 91-126.

Ming, X., Cao, M., Lv, X., Yin, H., Li, L. and Liu, Z., (2020). “Effects of high temperature and post-fire-curing on compressive strength and microstructure of calcium carbonate whisker-fly ash-cement system.” Construction and Building Materials, 244, Article ID 118333.

Miyatani, K., (2004). “On the use of lime in joint mortar of masonry buildings in the Meiji era.” AJI Journal of Architecture and Planning, 585, 169-176. (in Japanese)

Okada, K., Kobayashi, K. and Miyagawa, T., (1988). “Influence of longitudinal cracking due to reinforcement corrosion on characteristics of reinforced concrete members.” ACI Structural Journal, 85(2), 134-140.

Park, S. J., Yim, H. J. and Kwak, H. G., (2015). “Effects of post-fire curing conditions on the restoration of material properties of fire-damaged concrete.” Construction and Building Materials, 99, 90-98.

Phan, L. T., (2008). “Pore pressure and explosive spalling in concrete.” Materials and Structures, 41(10), 1623-1632.

Poon, C. S., Azhar, S., Anson, M. and Wong, Y. K., (2001). “Strength and durability recovery of fire-damaged concrete after post-fire-curing.” Cement and Concrete Research, 31(9), 1307-1318.

Shachar, Y. M. and Dancygier, A. N., (2020). “Assessment of reinforced concrete slabs post-fire performance.” Fire Safety Journal, 111, Article ID 102932.

Shah, A. H. and Sharma, U. K., (2017). “Fire resistance and spalling performance of confined concrete columns.” Construction and Building Materials, 156, 161-174.

Shang, X. Y., Yu, J. T., Li, L. Z. and Lu, Z. D., (2020). “Shear strengthening of fire damaged RC beams with stirrup reinforced engineered cementitious composites.” Engineering Structures, 210, Article ID 110263.

Suh, H., Jee, H., Kim, J., Kitagaki, R., Ohki, S., Woo, S., Jeong, K. and Bae, S., (2020). “Influences of rehydration conditions on the mechanical and atomic structural recovery characteristics of Portland cement paste exposed to elevated temperatures.” Construction and Building Materials, 235, Article ID 117453.
Tatsuki, S., Tsuyoshi, T., Ishibashi, T., Matsuda, Y. and Imai, T., (2007). “An experimental study on load-carrying capacity of RC members by alkali-silica reaction.” *Doboku Gakkai Ronbunshu E*, 63(1), 166-177. (in Japanese)

Toongoenthong, K. and Maekawa, K., (2004). “Multimechanical approach to structural performance assessment of corroded RC members in shear.” *Journal of Advanced Concrete Technology*, 3(1), 107-122.

Vance, K., Falzone, G., Pignatelli, I., Bauchy, M., Balonis, M. and Sant, G., (2015). “Direct carbonation of Ca(OH)$_2$ using liquid and supercritical CO$_2$: implications for carbon-neutral cementation.” *Industrial & Engineering Chemistry Research*, 54(36), 8908-8918.

Yasue, T. and Arai, Y., (1995). “Crystal shape and size controls of lime.” *Journal of the Society of Inorganic Materials, Japan*, 2(258), 356-364. (in Japanese)

Yoneda, T., Ishida, T., Maekawa, K., Gebreyouhannes, E. and Mishima, T., (2015). “A micro-cracking model coupled with micro fracture and water status in micro pore structures.” *Journal of Japan Society of Civil Engineers, Ser. E2*, 71(3), 263-282. (in Japanese)

Zhang, H. L. and Davie, C. T., (2013). “A numerical investigation of the influence of pore pressures and thermally induced stresses for spalling of concrete exposed to elevated temperatures.” *Fire Safety Journal*, 59, 102-110.

Zhang, Y., Zeiml, M., Maier, M., Yuan, Y. and Lackner, R., (2017). “Fast assessing spalling risk of tunnel linings under RABT fire: From a coupled thermo-hydro-chemo-mechanical model towards an estimation method.” *Engineering Structures*, 142, 1-19.