Preventive measures against cracks on concrete structures in design stage

Takayuki NISHIDO 1, Yutaka KAWANO 2
1 IHI Inspection & Instrumentation Co., Ltd, Yokohama, Japan; Phone: +81 45 791 3522, Fax +81 45 791 3547; e-mail: t_nishido@iic.ihi.co.jp
2 IHI Inspection & Instrumentation Co., Ltd, Yokohama, Japan; e-mail: y_kawano@iic.ihi.co.jp

Abstract
To avoid cracks for thermal stresses, engineers must consider to lower concrete temperature by curing and to add the number and sizes of reinforcing bars. The authors paid attention to solar radiation, because it rises the surface temperature of concrete structures more than external temperature. To investigate the influence exactly, a specimen was made. As the measured temperatures, strains and stresses after curing varied much than these during curing, the occurred tensile stresses may exceed the tensile strength. The Japan Meteorological Agency announces the highest, the lowest and the mean temperatures and the mean global solar radiation per one-month in every year. By using those data in the nearest to construction sites, the authors proposed to analyze temperature stress occurring in concrete structures at the same accuracy as the case of using measured data. Crack widths can be measured by using optic fiber cables on construction sites.

Keywords: concrete cracks, solar radiation, thermal stress analysis, concrete slab, optic fiber cable

1. Introduction
Water and salt through cracks on concrete structures corrode reinforcing bars, so countermeasures for cracks are needed at design and construction stages. To avoid the cracks for thermal stresses, engineers must consider to lower concrete temperature by curing and to add the number and sizes of reinforcing bars. Thermal stress analysis is usually done using external temperatures around concrete structures. The authors paid attention to solar radiation, because it rises the surface temperature of the concrete structures more than external temperature. To investigate the influence exactly, a specimen (concrete deck with steel girders) was made. External temperatures and the values of solar radiation were measured near the specimen.

Temperatures, strains and stresses in the specimen were also measured. As the measured those values after curing varied much than those during curing, the occurred tensile stresses by the cause of the variations may exceed the tensile strength. The analysis considering solar radiation as virtual external temperatures could express the phenomena of the specimen after curing [1].

Although external temperatures and the values of solar radiation can be measured at the experiment, it is impossible to do these data on construction sites at design stages. The Japan Meteorological Agency has announced the highest, the lowest and the mean temperatures and the mean global solar radiation per one-month in every year. By using those data in the nearest to the construction site, the authors proposed to analyze temperature stress occurring in concrete structures at the same accuracy as the case of using measured data. Engineers can take accurate preventive measures against harmful cracks in design stages by using the proposed method. Crack widths can also be measured by using fiber optic cables on construction sites.

2. Experiment
A specimen consisted of a concrete deck and two steel girders as shown in Fig. 1. Curing continued 7 days and then sunshine cutting sheets were used to remove the effect of solar
radiation except the surface of the concrete slab. The specimen was supported simply at the both ends.

![Figure 1. Specimen and measured condition](image)

![Figure 2. Section of specimen](image)
The section of the specimen is shown in Fig.2. The sizes of primary and distribution reinforcing bars were D16. Their pitches were 250mm, and the covers were 50mm or 30mm, respectively. Studs (φ19×150) with heads were used for composite between the concrete deck and the steel girders. The requirements for mixture in the concrete decks are shown in Table 1, and portland cement was used. As shown in Fig. 2, external temperatures in shade and values of solar radiation were measured at every an hour after placing near the specimen. Temperatures, strains and stresses in the concrete deck were also measured at the same intervals.

### Table 1. Requirements for mixture in concrete deck

<table>
<thead>
<tr>
<th>Specified design strength (N/mm²)</th>
<th>Slump (cm)</th>
<th>Air content (%)</th>
<th>Maximum coarse aggregate (mm)</th>
<th>Minimum unit cement content (kg/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>8±2.5</td>
<td>4.5±1.5</td>
<td>20</td>
<td>300</td>
</tr>
</tbody>
</table>

### 3. Analysis conditions

Material properties for analysis show in Table 2. Actual compressive and tensile strengths in the specimen at 28 days were 38.4 and 3.2 N/mm², respectively. The analysis was done by ASTEA MACS [2] that is FEM program to treat nonlinear thermal stress for concrete structures. Solid elements were used for the analysis as shown in Fig. 1. Weather factors on concrete structures are global solar radiation, atmospheric radiation, heat and water vapor convection. Thermal stress analysis usually considers only the convection as the surface temperature of concrete structures. We have often experienced the surface temperature of concrete structures was higher than external temperature on clear sky days. It is mainly for global solar radiation. Therefore the authors considered the both effects of the convection and the radiation as virtual external temperature defined as equation (1), in which the first term is the convection and the second term is the radiation.

\[ T_{eq}(t) = T_0(t) + \frac{q}{\mu} \]

Where \( T_{eq} \) virtual external temperature [°C], \( T_0 \) shade temperature [°C], \( q \) value of solar radiation [w/m²], \( \mu \) heat transfer coefficient [w/(m² °C)], \( t \) time (hours).

### Table 2. Material properties for analysis

<table>
<thead>
<tr>
<th>Items</th>
<th>Units</th>
<th>Values / Equations</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of thermal</td>
<td>/°C</td>
<td>10×10⁴</td>
<td></td>
</tr>
<tr>
<td>expansion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressive strength</td>
<td>N/mm²</td>
<td>( f'(t) = {t/{a+b(t)} \cdot f'(28)} \cdot d )</td>
<td>( a,b,d ) : Coefficient according to cement types</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>N/mm²</td>
<td>( f'(t) = 0.44 \cdot \sqrt{f'(28)} )</td>
<td></td>
</tr>
<tr>
<td>Young's module</td>
<td>N/mm²</td>
<td>( E_e(t) = 4700 \cdot \sqrt{f'(28)} )</td>
<td></td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td></td>
<td>0.18</td>
<td></td>
</tr>
</tbody>
</table>

As the surface of the concrete slab received sunshine after the curing, the second term was considered from 8th day. The heat transfer coefficient was 40 w/(m² °C) at wind velocity 2m/s on the surface according to the result of experiment [3]. The virtual external temperatures
were input on its surface. External temperatures ($T_0$ in equation (1)) were input on the places except the surface.

Fig. 3 shows the virtual external temperatures and the surface temperatures that were measured from 11:33 on 10/16 in 2007 during two weeks. The external temperatures ($T_0$) varied about 10°C per a day, and the virtual external temperatures ($T_{eq}$) added more about 15°C with the effect of solar radiation on the clear sky days. The surface temperatures on the specimen were higher than the external ones after curing (10/24). Weathers on 10/23, 10/24 and 10/25 were rain, cloud and fine. Their maximum values of solar radiation were 60, 506 and 692 w/m², and their converted temperatures were 1.5, 12.6 and 17.3 °C, respectively. From these results, the weather condition is an important factor for thermal stress analysis.

\[ T_{eq} = T_0 + \frac{q}{\mu} \]

4. Results and considerations

4.1 Temperatures

Fig. 4 shows the temperatures by the experiment and the analyses at the upper and the lower of the concrete deck as shown in Fig. 2. The blue lines were the analyses results by using the Metrological Agency data (M. A. data), which are explained in Chapter 5. Temperatures greatly varied after curing (10/24) for the effect of the solar radiation. The variations for a day at the upper were almost 10 °C and larger than those at the lower. The temperatures at the lower correspondence to the external temperatures ($T_0$) after curing as shown in Fig. 3. As the analyses could express the temperature variations after curing, the virtual external temperatures defined equation (1) is proper.
4.2 Strains

Fig. 5 shows the strains by the experiments and the analyses at the same positions of the measured temperatures. Strains greatly varied after curing (10/24) like the temperatures. Strains of the upper and the lower after curing by the analyses varied around the same compressive strain (-50μ), but these by the experiment varied around different strains (-25μ, -100μ). The same coefficient of thermal expansion used in the analyses might be cause of them.

![Figure 5. Strains](image)

4.3 Stresses

Fig. 6 shows the stresses by the analyses at the lower and the upper, and by the experiment and the analyses at the center. Tensile stresses occurred at the lower caused by constrain. The maximum variation for a day (10/25) was about 0.3 N/mm². Compressive stresses occurred at the upper and the maximum variation was about 0.6 N/mm². At the center, the maximum variation for a day (10/25) was about 0.9 N/mm² in the experiment and about 0.6 N/mm² in the analyses, respectively. From the results, cracks would occur at actual structures in two weeks after placing, if constraint conditions and the amount of heat generation were severer than the experiment.

![Figure 6. Stresses](image)

Fig. 7 shows the transformations of the specimen on 10/25 at 14:33 and on 10/26 at 4:33 in Fig. 3. The surface of the concrete deck expanded and shrank caused by the virtual external temperatures. Studs on the girders constrained the transformations, so the tensile stresses occurred at the lower of the concrete deck as shown in Fig. 6. Engineers can consider the influence of solar radiation using thermal stress analysis at design stages. They can also
manage to avoid cracks on concrete structures by adding the number and the sizes of reinforcing bars and extending the period of curing until the occurrence of expected tensile strength.

5. Analysis using database

The analyses considering the virtual external temperatures can simulate concrete internal temperature, strain and stress. Although external temperatures and the values of solar radiation can be measured in every an hour for the experiments, it is impossible to do those data on construction sites at design stages. The authors proposed to make the virtual external temperatures using the Japan Meteorological Agency database by internet.

5.1 Meteorological Agency data

From the homepage of the Japan Meteorological Agency [4], mean values of weather data in every day, every month and every year from 1981 to 2010 in 68 places in Japan can be obtained. Table 3 shows the temperatures (high, low and mean) and the mean global solar radiations at every month in Tokyo. Those data in October were used, because Tokyo is the nearest in the 68 places from Ayase city, where the experiment were done.

5.2 Approximation method to experimental values

The measured values of solar radiations at every hour were used in the experiment. Similarly, they could be calculated by the global solar radiations of the Japan Meteorological Agency. Fig. 8 shows the approximate solar radiations with half sine waves and the measured values at every hour from 10/24 to 10/26. The maximum values of the half sine waves were decided, as the amounts of the approximate solar radiations coincided with the ones of the measured values. The good approximation could be obtained to set the half sine wave in 8 hours and zero in residual 16 hours. Fig. 9 shows the result in applying the approximate method to the values of solar radiation during 12 days from 10/24 to 11/5.

It is the simplest to use the mean temperature (e.g. 20°C) of a day for external one. However, the variation of a day is about 10°C according to Fig. 3, it is underestimated to use the mean temperature. Therefore, the authors proposed to repeat at 24-hour intervals between the highest temperature (21.5°C, 12:00) and the lowest temperature (14.2°C, 24:00) as shown Fig.10.
The virtual external temperatures by using both the Japan Meteorological Agency data and the experiment are shown in Fig. 11. They were almost same at the low temperatures, but they had differences at the highest temperatures on 10/23 and 10/24, in which the former was rain and the latter was cloud. Because the Japan Meteorological Agency data is the mean values for a month, it is impossible to consider the weather conditions.

Table 3. The Japan Meteorological Agency data in Tokyo

<table>
<thead>
<tr>
<th>Period</th>
<th>Mean</th>
<th>High</th>
<th>Low</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>5.2</td>
<td>9.6</td>
<td>0.9</td>
<td>8.9</td>
</tr>
<tr>
<td>Feb</td>
<td>5.7</td>
<td>10.4</td>
<td>1.7</td>
<td>10.9</td>
</tr>
<tr>
<td>Mar</td>
<td>8.7</td>
<td>13.6</td>
<td>4.4</td>
<td>12.5</td>
</tr>
<tr>
<td>Apr</td>
<td>13.9</td>
<td>19.0</td>
<td>9.4</td>
<td>15.3</td>
</tr>
<tr>
<td>May</td>
<td>18.2</td>
<td>22.9</td>
<td>14.0</td>
<td>16.2</td>
</tr>
<tr>
<td>Jun</td>
<td>21.4</td>
<td>25.5</td>
<td>18.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Jul</td>
<td>25.0</td>
<td>29.2</td>
<td>21.8</td>
<td>14.6</td>
</tr>
<tr>
<td>Aug</td>
<td>26.4</td>
<td>30.8</td>
<td>23.0</td>
<td>15.2</td>
</tr>
<tr>
<td>Sep</td>
<td>22.8</td>
<td>26.9</td>
<td>19.7</td>
<td>11.1</td>
</tr>
<tr>
<td>Oct</td>
<td>17.5</td>
<td>21.5</td>
<td>14.2</td>
<td>9.6</td>
</tr>
<tr>
<td>Nov</td>
<td>12.1</td>
<td>16.3</td>
<td>8.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Dec</td>
<td>7.6</td>
<td>11.9</td>
<td>3.5</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Figure 8. Solar radiations of experiment and approximations during 3 days
5.3 Validity of proposal approximation method

Fig. 4, 5 and 6 show the results of temperatures, strains and stresses by using the Japan Meteorological Agency data (blue lines), the measured solar radiation (red lines, $T_{eq}$) and the experiment (black lines). The Japan Meteorological Agency data in the temperature on 10/23 and 10/24 were higher than the experiments as shown in Fig. 4, because they could not consider the weather conditions as mentioned earlier. Therefore, the analysis using the mean data for a month will be safe estimation at design stages. The three results were almost same after 10/25.

As shown in Fig 5 and 6, the results of strains and stresses in both the Japan Meteorological Agency data and the measured solar radiations were the same tendency with the temperatures. This study was used the mean values for a month, but the differences would be little if the mean values for 10 days or a day were used. It is possible for designers to get sufficient measures for cracks easily and precisely at design stages by using the mean values for a month.

6. Measurement for cracks on actual bridges

The measurement for cracks may be necessary on construction sites. The authors have proposed to use SOFO sensor (Surveillance d'Ouvrages par Fibres Optiques), which is a measuring displacement system using optical fiber cables. It is composed of two optical fibers
as shown in Fig. 12. As the measuring fiber is added tension force in advance, it expands and contracts in response to the deformation between two points fixed at structures. The other is the reference fiber in spiral, of which length is not affected by the deformation between the fixed points. The SOFO sensor measures the difference between the two optical fibers.

![Diagram of SOFO sensor components]

**Figure 12. SOFO sensor**

The resolution of the SOFO sensor is 2mm regardless of optical fiber cables’ length. It is buried in concrete structures or is mounted on the surfaces of ones as shown in Fig. 13. The optical fiber cables can be extended up to 5km.

Although the PI displacement transducer had to be set to step over a crack as shown in Fig. 14, the SOFO sensor could measure any crack width in an optical fiber cable. Its error to the transducer on a measured crack width became less than 10% [5]. It is thought that the SOFO sensor has enough performance as a crack width measurement one for concrete structures.

![Images of SOFO sensor and PI displacement transducer]

**Figure 13. SOFO sensor on concrete structure**

**Figure 14. Experiment with SOFO sensor and PI displacement transducer**

### 7. Conclusions

Temperatures, strains and stresses by the experiment after curing varied greatly than those during curing. The analyses for temperatures, strains and stresses by using virtual external temperatures, which were made of shade temperatures and values of solar radiation for every one hour, could simulate the phenomena of concrete slab after curing.

The solar radiation greatly affects concrete internal temperature, strain and stress. Therefore, there are possibilities of crack occurrences on the surface of concrete decks by the cause of the amount of heat generation and constraint conditions.
The good approximation could be obtained to set values of solar radiation as half sine wave by using the mean values for a month of the Japan Meteorological Agency data. It is possible for designers to get sufficient measures for cracks easily and precisely at design stages.

If SOFO sensor were used for crack width measurements on concrete structures, the same precision as PI displacement transducer could be obtained, and unexpected cracks at any positions in an optical fiber cable could be measured.

References
2. 'ASTEA MACS for windows Ver.4 Training note', Research Center of Computational Mechanics, Inc., 2007.