PRESTRESSED CONCRETE BEAM CONSTRUCTION PRACTICE

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This study's purpose was to determine maximum temperature gradients and rate of temperature change, through the cross-section of a prestressed, precast concrete I-beam, throughout the construction and curing periods during winter fabrication. The study resulted from the observation that slight cracking appearing on some prestressed beams might be resulting from rapid or differential changes in temperature during curing under current winter practice. The project was initiated by W. W. McLaughlin on October 8, 1962.

Subsequent visits to several plants by Testing and Research personnel resulted in selection of American Prestressed Concrete Inc. of Centerline, Michigan, as the site for the tests. Approval from George DeClerk, owner of the company, was obtained on January 7, 1963, and on February 27, Research Laboratory personnel from the Instrumentation and Data Systems Unit installed 14 thermocouples in Beam No. 3C18 at locations shown in Fig. 1, and one each to record air temperature inside and outside the steam enclosure. The thermocouples were connected to a 16-point temperature recorder in a nearby instrument trailer, and readings were taken from the time of concrete placement until the web of the beam had cooled to near air temperature about 47 hr later. Temperature is plotted against time for points in the web section and anchorage block section in Figs. 2 and 3, respectively.

Discussion of Specifications in Relation to Test Results

In Departmental Supplemental Specifications dated May 1, 1961 (Section 5.01.15(e), "Curing of Prestressed Concrete Beams") the following requirements were listed:

1. "The concrete shall have a temperature of not less than 50 F, nor more than 85 F, and shall be as near 70 F as practical at the time of placing in the forms. Concrete shall be protected in such a manner as to prevent damage from cold weather.

2. "Steam for curing the beams shall be available at all times during the curing period so as to maintain the required temperature.

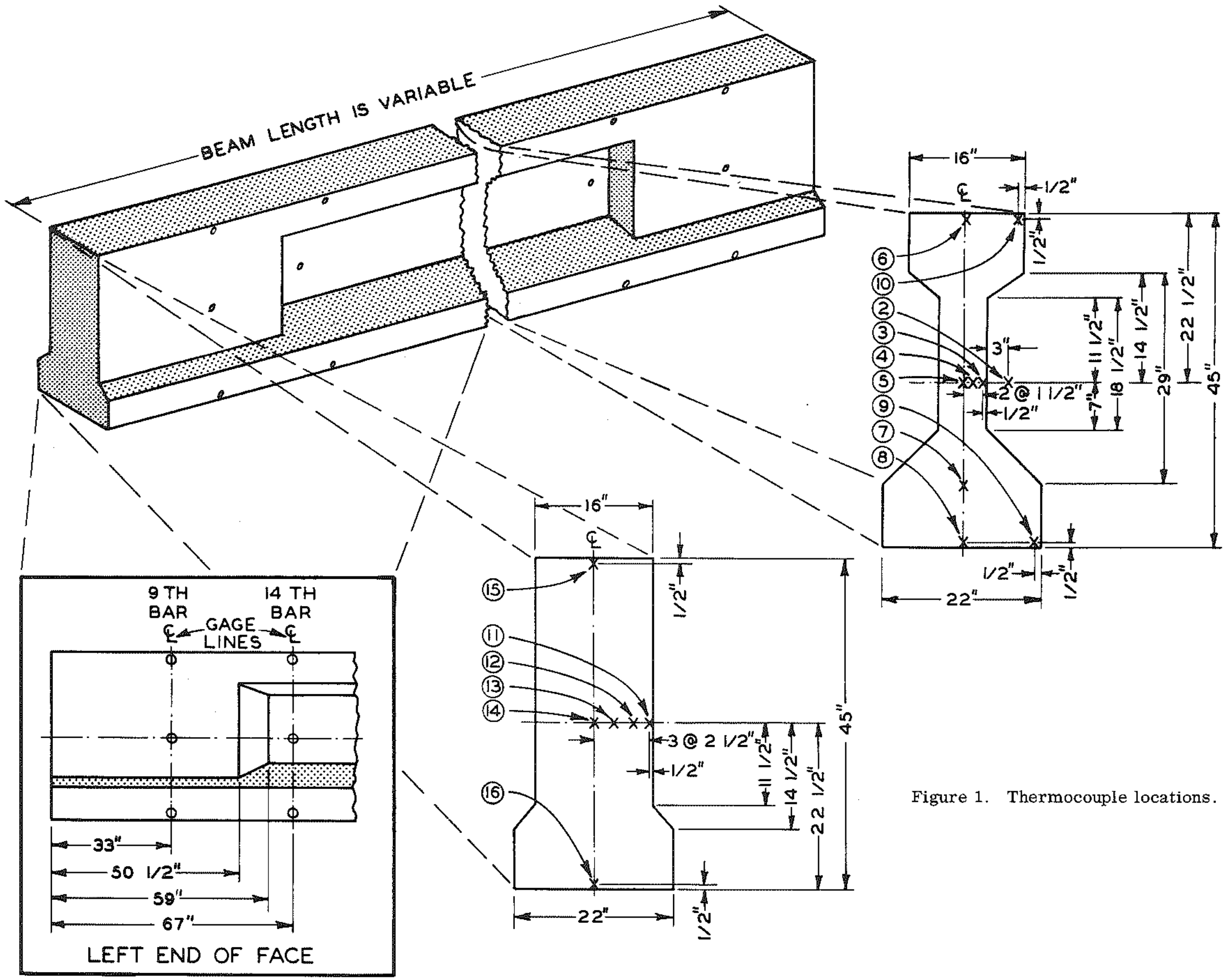

Figure 1. Thermocouple locations.

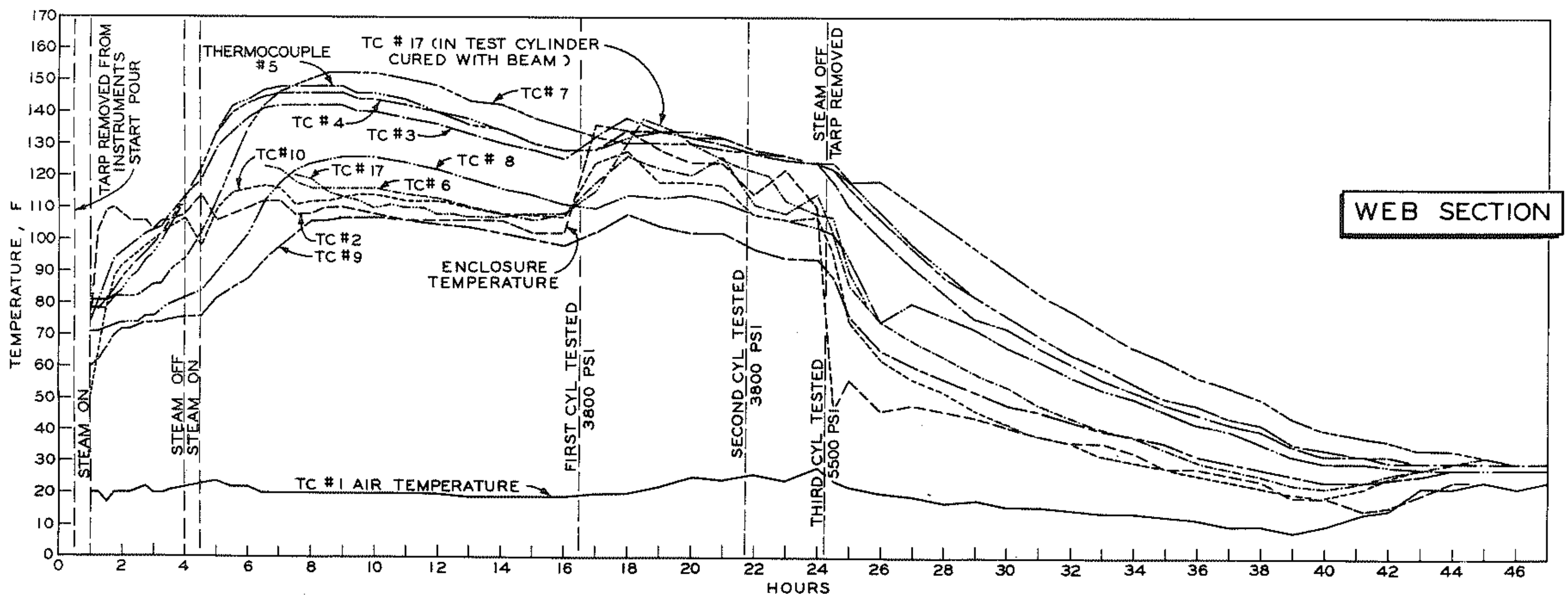

Figure 2. Time vs. temperature for thermocouples in beam web section.

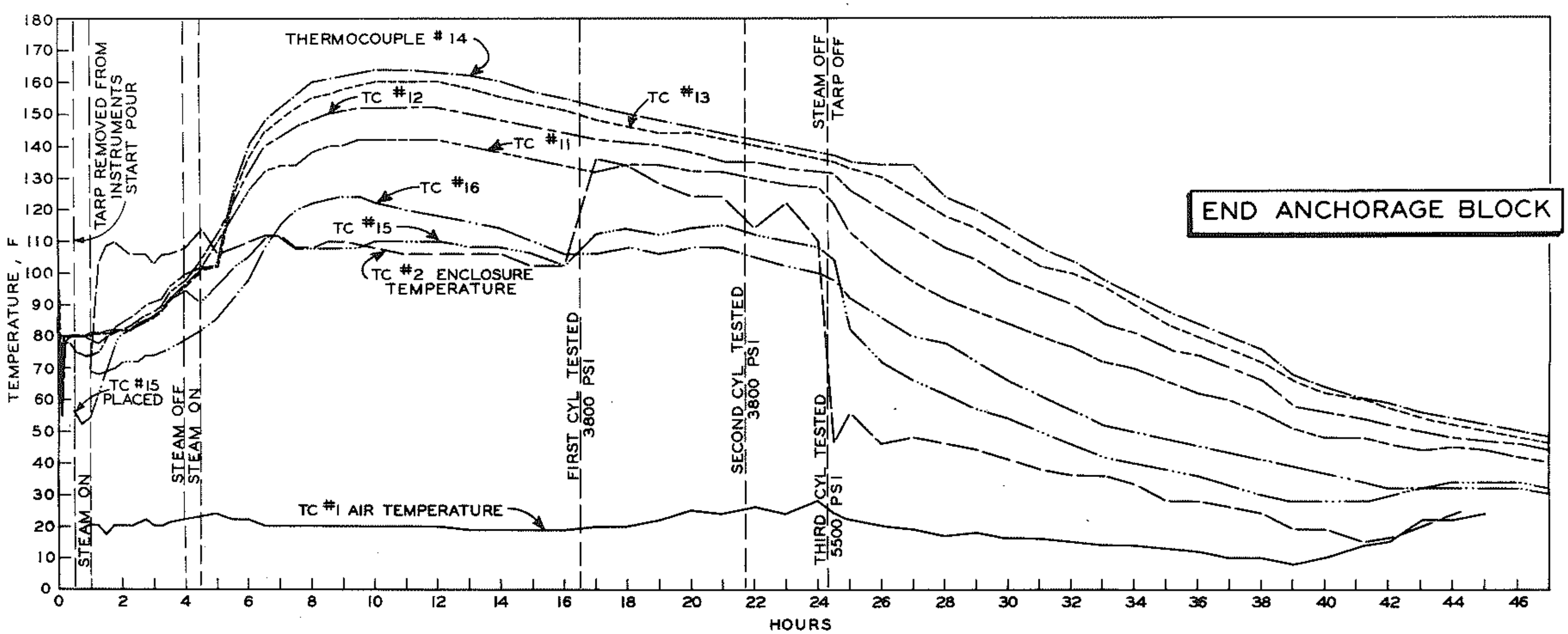

Figure 3. Time vs. temperature for thermocouples in beam end anchorage block section.

3. "The beams shall be cured at a temperature between 70 and 145 F, ± 5 deg, until the concrete attains a strength of not less than 4000 psi as determined by the test cylinders cured in the same manner as the beams....

4. "When free steam is used for curing the beams, the temperature of the concrete shall be raised to the designated curing temperature at a rate of not more than 1/2 deg per min, and the temperature of the concrete shall not exceed 145 F.

5. "The maximum curing temperature, between 70 and 145 F, shall be designated by the manufacturer of the beams before starting the placing of concrete. During the period of the maximum curing temperature, the designated temperature shall be maintained within a tolerance of ± 5 deg.

6. "The temperature of the concrete shall be lowered from the maximum curing temperature to the atmospheric temperature at a uniform rate of not more than 1/2 deg per min."

The following comparisons of the Laboratory's test with these specifications are made with reference to Figs. 2 and 3:

1. Concrete temperatures at the beginning of the steam period ranged from 50 F at location 10, to 81 F at locations 7, 13, and 14, with most of the early recordings in the 68 to 81 F range, which is within the specified limits.

2. Steam for beam curing was available at all times.

3. It was assumed here that the specified "curing temperature" refers to the enclosure temperature and not the actual concrete temperature. Recordings from Thermocouple 2 in Figs. 2 or 3 show that the steam chest temperature varied widely and did not comply with requirements. At an age of about 16 hr, the steam control was turned up and the enclosure temperature rose 34 deg in 1 hr, then fluctuated with a gradual decrease until shut-off.

4. In most locations the temperature rise was within the specified 1/2 deg per min. Thermocouples 13 and 14 recorded increasing temperature rates of 34 and 38 deg, respectively, during the sixth hour of curing, but these rates are not considered excessive. An experiment reported by J. A. Hanson[1] indicated an optimum temperature rise rate of 40 deg per hr for an initial enclosure temperature of 76 F. The part

of the third requirement dealing with a maximum enclosure temperature of 145 F seems incompatible with the fourth requirement, since the heat of cement hydration will almost certainly cause the concrete temperature to exceed the maximum allowed (145 F). Suffice it to say here that the temperature of the test beam's interior did rise to 164 F, which is 19 deg above the maximum specified limit. However, this is not in itself considered detrimental.

5. As has already been commented, the tolerance of $\pm$ 5 deg on maximum "curing temperature" was not maintained.

6. The specified rate of temperature drop was evidently maintained, except for the surface near Thermocouple 6 which registered a drop of 33 deg during the hour after steam and enclosure were discontinued. Steam curing of the test beam, was discontinued at a compressive strength of 5500 psi, with the temperature of the beam interior then near 135 F. From this point, the assembly was cooled to about 25 F before the cables were cut. Section 5.13.03.a, Paragraph 6 ("Curing of Beams") of the 1965 Specifications has been only slightly modified from the 1961 Supplemental Specification. The intent of the current specification seems to be that the enclosure temperature should be controlled at some temperature between 70 and 145 F, since control would be practically impossible at every point in the beam to any specific value, because of heat generation and temperature rise due to cement hydration. Wording of the paragraph would be clearer if enclosure temperature were specified. Figs. 2 and 3 show that the beam's interior temperature is influenced only slightly by the enclosure temperature, during the period of temperature rise due to hydration. Even though the enclosure temperature is relatively constant at 110 F, the interior concrete temperature rises quickly to the 150 to 165 F range.

The 1965 specification states that concrete temperature shall be raised to the designated curing temperature at a rate of not more than 1/2 deg per min, and the temperature of the concrete shall not exceed 145 F. It should be pointed out that the inspector on a job has no way of knowing what the maximum concrete temperature is, unless thermocouples are placed at numerous locations in each beam. Enclosure temperature is much more easily measured in the field than concrete temperature. It would seem more reasonable to specify control of a quantity that is easily measured. J. A. Hanson,[1] who has conducted numerous experiments on test cylinders, found optimum results with temperature rise in steam-cured cylinders of about 40 deg per hr up to a constant temperature of 150 F. Concrete temperature rise rate exceeded steam room rise rate by 10 deg per hr, and enclosure temperature rise rates of 60 deg per hr caused surface cracking. Heating too quickly after casting was found to be detrimental. It should be noted here that test cylinders are much more quickly influenced by surrounding temperature than is a massive structure like a beam, and that temperature maxima would be lower in a cylinder than in a beam subjected to the same environment. It is recommended that the wording of this paragraph be changed somewhat to read in the following manner (which is very close to the wording of Section 6.04 of the State of North Dakota's new Standard Specifications for Road and Bridge Construction): "Enclosure temperature shall not exceed 90 F for at least 2 hr after casting, and shall then be raised at a rate not to exceed 25 deg per hr to a maximum of not more than 145 F, and held constant (± 5 deg) until specified strength is obtained. Cables must then be cut in the specified manner before the surface temperature of the beam has decreased 20 deg, and subsequent cooling shall not exceed 20 deg per hr."

Beam Curing

Before proceeding with particulars of this study, it might be well to make some general remarks about the process of concrete curing. As curing proceeds, the concrete generally rises in temperature due to the heat of hydration of the cement, and changes from a soft, yielding material to a rigid, somewhat elastic material. Only a moderate degree of compressive stress develops from the restrained thermal expansion because of the plasticity of the young concrete.[2] Sustained exposure to the high temperature causes considerable gain in strength and loss of plasticity. It seems reasonable, then, to assume that the bond between concrete and steel prestressing wires in a prestressed beam would be formed at or near the beam's maximum curing temperature. Then, if the beam is allowed to cool without releasing the wires from their anchorage, they will form a definite restraint to contraction of the concrete, causing tensile stresses to develop.

Tensile stress is also induced in the surface of the beam because of a temperature differential between its surface and interior during cooling. Also, since surface temperatures have been somewhat lower during curing, it is doubtful whether the surface has developed as much strength as the interior of the beam. In the Laboratory's beam test, the air temperature was about 90 deg below beam surface temperature when protection was removed, causing a temperature differential from surface to interior of about 50 deg (Figs. 2 and 3). Stress relief by plastic flow cannot readily occur, once the concrete has cured, and if at any time tensile stress exceeds tensile strength of the surface concrete, cracking will occur.[2] It is impossible to determine the state of stress in the beam before cooling began, because of plastic adjustments during early curing. The fact remains, however, that conditions were present tending to cause cracking, and measures to prohibit these conditions should be initiated in future fabrications.

Cutting the cables before cooling starts puts the beam into compression, and eliminates the restraint to normal contraction at the steel level, thus minimizing induced tensile stresses which could cause cracking. The 90 F holding temperature for 2 hr after casting gives cold weather protection to the surface of the beam without the detrimental effects of early heating. The 25 deg per hr limit on temperature rise rate in the enclosure seems a reasonable compromise between extremely slow heating, and a high temperature rate that might tend to push the rate of internal temperature increase above the recommended 40 deg per hr. Hanson found that temperatures even above 175 F were not detrimental to concrete strength if the rate of temperature rise was not more than 40 deg per hr.

Test Cylinder Curing

Thermocouple 17 was installed in a test cylinder that was cured with the beam. Due to trouble with switches in the hook-up wiring, valid readings from this thermocouple were not obtained for about 7 hr after the beam was cast. Fig. 2 shows that the cylinder temperature followed enclosure temperature quite well in the interval where readings could be made, and was within the range of temperatures experienced by various parts of the beam. Due to the smaller mass of the cylinder, it would undoubtedly respond more quickly than the beam to the initial rise in temperature within the enclosure.

Test cylinders should be placed so as to experience some reasonable average of the maximum and minimum temperatures existing within the enclosure. The strength of the cylinder must be relatively representative of concrete strength in the beam, if cylinder tests are to be useful. Curing of two specimens so different in size as a test cylinder and a bridge beam will result in different strength-time characteristics, when exposed to the same environment. The fact that the cylinder will experience a lower maximum temperature and follow enclosure temperature more closely than the beam interior, should lead to test results that are conservative or "safe."

Conclusions

This study has shown that undesirable temperature gradients were developed in the beam during cooling. The net effect of the cooling process is to induce tensile stresses in the concrete, whenever there is any restraint to the normal contraction that would otherwise occur. Induced tensile stresses are the cause of cracking, and should be prohibited to the greatest extent possible.

It is concluded that Article 5.13.03. a, Paragraph 6 ("Curing of Beams") of the current specifications should be revised, incorporating the results of this study and emphasizing the importance of cable release prior to a period of controlled, gradual cooling. Based on this study and subsequent discussions with the Field Testing Division concerning current fabricating practice, the following suggested revision is presented with supplemental explanatory comments in parentheses:

6. Curing of Beams. --The concrete shall have a temperature of not less than 50 F, nor more than 75 F, and shall be as near 70 F as possible at the time of placing in the forms. Concrete shall be protected in such a manner as to prevent damage from cold weather. The housing shall be so constructed as to allow free circulation of air or steam around the beam. (The upper initial concrete temperature was changed from 85 to 75 F to be compatible with the requirements of Article 5. 01. 03. k.)

The beams shall be cured at an enclosure temperature between 70 and 150 F until the concrete attains a strength of not less than 4000 psi as determined by test cylinders cured in the same manner as the beams. Steam for curing the beams shall be available at all times during the curing period. (The upper temperature limit was changed from 145 to 150 F to be compatible with a 150 F maximum enclosure temperature specified later. This paragraph could contain a definition of how and where the enclosure temperature is to be measured, and also when the test cylinders will be placed inside the enclosure. Since the enclosure temperature around any beam is going to vary, it is suggested that enclosure temperature be determined as the average of at least four temperature observations at mid-height of the beam, at each end, and on each side. Also, the location of the test cylinders could be defined--e. g. , at the mid-height of the beam near the center of the beam span.)

When free steam is not used for curing the beams, the exposed surfaces of the beams shall be cured as specified under "Concrete Bridge Construction" (5. 01. 03. j).

When free steam is used for curing the beams, the steam shall be uniformly distributed throughout the enclosure but not jetted directly on the concrete. The initial enclosure temperature shall not exceed 90 F for a minimum of two hours after casting. After the minimum two-hour presteaming period, the enclosure temperature shall be raised to a level not exceeding 150 F at a temperature rise rate not greater than 25 deg per hour. (The important point here is to minimize potential cracking resulting from high temperature gradients during the temperature rise period and subsequent expansion of the plastic concrete prior to initial set. Temperature observations every 15 minutes during this temperature rise period should be sufficient to establish the necessary control of the temperature gradient. This could also be stated in the specification.)

The beams shall then be cured at an enclosure temperature between 70 and 150 F until the concrete attains the required strength. During this curing period the enclosure temperature gradient shall not exceed ±10 deg per hour. (During this constant temperature phase of curing, it is important to minimize large temperature fluctuations not only for efficient curing for early strength, but also to minimize large temperature gradients within the beam.

After the required beam compressive strength has been established, the pretensioned strands shall be cut in the specified manner before the surface temperature of the concrete has dropped 20 deg. Subsequent cooling of the enclosure atmosphere shall not exceed 20 deg per hour until the enclosure temperature is within 20 deg of the air temperature to which the beams will be exposed. (Immediate cutting of the strands will do two things: remove the restraint to the concrete at the steel level as the concrete contracts with cooling, and, coupled with the dead load stress at cable release, place a large percentage of the beam in compression. In order to do this, the fabricator would have to provide individual steam control for each beam. He would have to do this anyway, since in a very long casting bed requiring more than about four hours to complete concrete placement, the first-poured beams would have to start steam curing as the specified enclosure temperature conditions have to apply to each beam in the bed. He would also have to provide additional tarps at all bulkhead locations in the beam bed for access to the cables. Further, the fabricator would have to remove the housing for each beam, one side at a time, to strip the side form and replace the housing, at the same time maintaining the enclosure temperature in all other locations along the bed. After the forms have been removed in this manner, the tarps could be removed from the bulkhead area and the strand cutting begun. As an alternate to this form stripping procedure, the fabricator could utilize forms that do not have to be removed in order to release the prestress.)

It should be noted that undesirable temperature gradients can and do occur in summer as well as in winter construction, since the heat of hydration may cause very high internal temperatures in a beam cured during hot weather. Care in cooling, coupled with proper timing of cable release, is a year-round requirement.

References

1. Hanson, J. A. Optimum Steam Curing Procedure in Precasting Plants. J. of the ACI, pp. 75-99, Jan. 1963.

2. Carlson, R. W. Temperatures and Stresses In Mass Concrete. J. of the ACI, pp. 497-515, March-April 1938.