

CHAPTER 3 – THERMAL BRIDGE DISPLACEMENTS

3.1. Introduction

A change in temperature causes a material to change in length. This fundamental property of materials is responsible for expansion and contraction of bridge superstructures. As the temperature increases, the bridge expands. As the temperature drops, the bridge contracts.

In conventional bridges, expansion joints exist between the superstructure and the abutment to accommodate these displacements. In integral bridges, the expansion joints are eliminated and the superstructure is allowed to freely displace the bridge abutments. Because of the abutment displacements, the pile and the approach fill are subjected to lateral loading and unloading.

This chapter first discusses the effects of temperature variation on integral abutment bridges. Next, practical treatment of these effects in the design stage is discussed. Finally, a procedure to consider both daily and seasonal temperature cycles in experimental testing is proposed.

3.2. Factors Affecting Bridge Temperatures

Structure temperatures at a locality are determined by continuously changing meteorological conditions. Although the meteorological conditions are very complex to fully understand, the primary factors that influence the structure temperatures can be summarized as follows (England et al., 2000; Moorty and Roeder, 1992; Potgier and Gamble, 1989; and Hoffman et al., 1983):

- diurnal temperature,
- solar radiation,
- wind speed,
- precipitation,
- thermal properties of structural material, and
- other weather conditions.

Diurnal temperature variation is one of the most important parameters to determine the bridge temperature. Meteorological institutions throughout the United States measure the air temperature in a standard manner without being affected by wind and other weather conditions.

The solar radiation is higher in sunny days and lower in cloudy days. For all things being equal, higher solar radiation means higher structure temperature and lower solar radiation means lower structure temperature. Potgieter and Gamble (1989) report existence of 89 solar stations across the United States. Some of these stations measure solar radiation directly while some collect relevant meteorological data so that solar radiation can be indirectly determined.

The wind speed is an indication of how the temperature at a locality is affected by the temperatures at surrounding locations. In other words, the wind factor changes the temperatures at a locality. In general, higher wind speed translates into lower structure temperatures.

Precipitation is also an important factor because of the existence of heat transfer between the structure and the precipitation falling on the superstructure. Additionally,

evaporation takes place, which reduces the heat stored in the superstructure, resulting in lower temperature. In general, precipitation reduces the structure temperature.

Thermal properties of the bridge superstructures are also an important factor because they control how the heat transfer takes place within the superstructure. Metals allow heat to flow faster than concrete does. For a given time and locality, structure temperature variation of metal bridges is higher than that of concrete bridges.

A combination of the factors discussed above (air temperature variation, the solar radiation, the wind speed, etc.) creates complex temperature distributions over the depth of a superstructure. Moorty and Roeder (1992) provide a theoretical discussion about the principal mechanisms of heat transfer in a bridge. Emerson (1977) discusses distribution of temperature over the bridge beams as shown in Figure 3.1. He concluded that the temperature in the upper part of the superstructure is mostly controlled by the solar radiation. The temperature in the lower part of the superstructure is affected by the shade temperature and the heat from the ground beneath the bridge. Weather conditions in the past few days govern the temperature in the middle region of the bridge superstructures.

Meteorological data (diurnal temperature, wind speed, solar radiation and precipitation) have been collected by various government sources. These sources include *Climatic Atlas of the United States* (1968), Solar Radiation Energy Resource Atlas of the United States (1981), and the National Climatic Center, Asheville, North Carolina. Additionally, South Carolina Department of Natural Resources Climate Service keeps temperature records of Virginia, North Carolina, South Carolina, Georgia, Alabama, and Florida.

3.3. Practical Treatment of Temperature Effects

Variation of the temperature through the bridge depth is handled in two parts:

1. Mean bridge temperature, and
2. Temperature gradient across the bridge depth.

According to Emerson (1977), and Black and Emerson (1976), the mean temperature, also called effective bridge temperature, is primarily responsible for the expansion and contraction of a bridge. AASHTO Standard Bridge Specifications (1996)

and AASHTO LRFD Specifications (1998) have conservative recommendations to calculate the mean bridge temperatures for both metal and concrete bridges.

The temperature gradient through the bridge depth is responsible for bending of bridge girders (Potgier and Gamble, 1989). Most of the time, the temperature distribution is not uniform across the bridge deck. This creates non-uniform strains above and below the neutral axis of the bridge girders, resulting in bending stresses in the bridge girders. AASHTO Guide Specifications for Thermal Effects in Concrete Bridge Superstructures (1989) has recommendations on how to obtain the temperature distributions and how to calculate the bending moment.

3.4. Prediction of Thermal Bridge Displacements

AASHTO Standard Bridge Specifications (1996) recommends a convenient and a simple way to estimate temperature-induced longitudinal displacements if no restrictions were imposed at the ends of the bridge deck, as shown by Equation 3.1. The reduction in bridge displacements due to approach fill resistance is assumed negligible; therefore, Equation 3.1 is also applicable to integral and semi-integral abutment bridges.

$$\Delta = \alpha(\Delta T)L_b \quad (3.1)$$

Where,

Δ = bridge displacement (expansion or contraction), same units as L_b ,

α = coefficient of thermal expansion, 0.0000065 / °F and 0.000006 / °F for steel and concrete bridges, respectively (AASHTO Standard Bridge Specifications, 1996),

ΔT = temperature difference between the effective bridge temperature and the construction temperature.

L_b = length of bridge from the neutral point (usually the center of the bridge) to abutment.

As it is evident by Equation 3.1, the detrimental effect of the temperature in integral bridges is due to the difference between the extreme temperatures of the bridge and the

construction temperature. In other words, a designer must estimate the maximum possible value for ΔT to predict the maximum expected bridge displacements.

AASHTO Standard Bridge Specifications (1996) recommends that the rise and the fall of the temperature be fixed with respect to the temperature at the time of installation for the locality where the structure is built. It also recommends that consideration be given to the lag between the air temperature and the inside temperature of massive concrete structures due to the reasons discussed earlier. Generalized yearly temperature variations for different bridge materials and for different climates are as follows (AASHTO, 1996):

For metal structures:

in moderate climate: 0 to 120 °F and in cold climate: -30 to 120 °F

For concrete structures:

in moderate climate: 30 °F temperature rise and 40 °F temperature fall

in cold climate: 35 °F temperature rise and 45 °F temperature fall

For metal structures, the designer must assume a construction temperature in order to determine the temperature fall and rise if the above recommendations of AASHTO are to be used. Transportation agencies usually do not limit the construction temperature when the girders and abutments should be placed. The contractor can make the integral connection at any working day of the year. In this case, it would be wise to consider the extreme weather conditions where the construction temperature is practically the highest and/or the lowest of the year. For concrete bridges, AASHTO implicitly assumes the construction temperature by specifying a temperature fall and rise.

As an alternative to assuming a construction temperature, a range of temperatures can be specified on the day when the integral connection is made. This would eliminate the uncertainty in the construction temperature, allowing designers to better estimate the temperature effects. The most useful implication in specifying a construction temperature range would be to build longer integral bridges. A metal bridge of length L constructed at 120° F, and another bridge of length $2L$ constructed at 60° F experience approximately the same maximum displacement if the air temperature varies between 0 and 120° F. However, the above alternative may not be practical for most cases.

3.5. Daily and Seasonal Variation of Thermal Bridge Displacements

Bridge displacements are affected by both daily and seasonal temperature changes. Each daily variation in temperature completes a cycle of expansion and contraction, and the cycles repeat over time. The greatest expansion takes place during summer days, while the greatest contraction occurs during winter nights. These extreme temperature variations control the extreme displacements of integral bridges. Figure 3.2 shows the temperature variation and the measured displacements at the abutment of the Maple River Bridge located in northwest Iowa, which includes some of the most complete and valuable data related to the performance of integral bridges. The Maple River Bridge is 98 m long and 10 m wide with a skew of 30 degrees. The bridge has three spans and consists of a composite concrete deck and steel girders. Two piers of the bridge are located about 30 m from each abutment.

As can be seen from Figure 3.2, the change in the ambient temperature completes one cycle for a given day, and the daily cycles ride on large seasonal cycles. The maximum expansion and the maximum contraction of the bridge coincide with the maximum and the minimum ambient temperatures.

It is also clear in Figure 3.2 that bridge displacements consist of daily small cycles and seasonal large cycles. In addition, the relationship between the air temperature and the bridge displacement appears linear as suggested by Equation 3.1.

Daily temperature range seems to vary throughout the year as seen in Figure 3.2. Figure 3.3 depicts the mean high, the mean low and the mean average values of temperatures obtained from records between 1948 and 1998 in Charlottesville, VA. This figure illustrates that, on average, the temperature varies between approximately 0°F to 90°F. In addition, the daily temperature variations range between 16°F to 41°F. In other words, daily temperature variations are between 18% to 45% of the seasonal variation of the air temperature.

Daily displacement cycles of bridges can be assumed to have a linear relationship with the annual bridge displacement. This assumption is supported both by Equation 3.1 (AASHTO Standard Bridge Specifications, 1996 recommendation) and data shown in

Figure 3.2. Under this assumption, one would expect that an integral bridge built in Charlottesville, VA should experience daily displacement variations that are equal to 18% to 45% of the maximum expected bridge displacement. Figure 3.3 indicates that daily variations are greater in the winter than they are in the summer. Similar findings were reported by Lawver et al. (2000). In their study, it was found that daily bridge displacements vary between 10% and 40% of the annual bridge displacements for a bridge in Minnesota. They reported that the lower end of the daily displacements was observed on July 15, 1997. Their experimental observations further support the significance of daily variations of the bridge displacements.

3.6. Proposed Modeling of Daily Temperature Variations in Experimental Research

An integral bridge experiences numerous cycles of expansion and contraction during its life. The maximum expansion takes place in the hottest day of the year while the maximum contraction takes place in the coldest day of the year. These displacements are the highest possible lateral displacements of a bridge due to temperature variations. Additionally, integral bridges are subjected to daily temperature cycles that are 365 times more than the seasonal cycles during the life of the bridge. The magnitudes of the daily temperature variations are not negligible as indicated in Figures 3.2 and 3.3. Both the magnitude and the number of daily cycles suggest that consideration should be given to daily displacement cycles in experimental research.

As discussed before, bridge displacements have a linear relationship with the temperature fluctuations. Therefore, it is reasonable to model the daily displacements based on the variations of daily temperatures.

For a given year, temperature range in a month is higher than the daily temperature range of a day in the same month. In other words, studying monthly temperature variations instead of daily variations is conservative. This is important because monthly temperature variations are significantly easier to obtain than daily variations. Therefore, it is reasonable to investigate the variation of monthly temperatures instead of daily temperatures.

3.6.1. Selection of Temperature Data

Southeast Regional Climate Center of South Carolina Department of Natural Resources has a web site that publishes temperature data collected at stations throughout the southwest United States, including the state of Virginia. Monthly temperature data of selected stations across the state of Virginia were downloaded from the agency's web site at <http://water.dnr.state.sc.us/climate/sercc>. Nine stations were selected to represent the temperature data across the state of Virginia. The following stations are deemed to represent a reasonable variation of temperature in Virginia: Blacksburg, Charlottesville, Danville, Norfolk, Richmond, Roanoke, Staunton, Washington National Airport, and Wytheville.

The raw data includes 30-year monthly normal values of temperature measured between 1961 and 1990. The difference between the maximum average and the minimum average temperature of each month provide the monthly temperature variation $\Delta T_{\text{monthly}}$. The values of $\Delta T_{\text{monthly}}$ for each station were obtained from the raw data and presented in Figure 3.4. As seen in the figure, the Wytheville station has the maximum $\Delta T_{\text{monthly}}$ values while the Norfolk station has the minimum $\Delta T_{\text{monthly}}$ values as expected. Wytheville is located in the Appalachian Mountains whereas Norfolk is located on the coast of Atlantic Ocean.

The minimum and the maximum values of $\Delta T_{\text{monthly}}$ values in Figure 3.4 are 15.3°F and 29.3°F, respectively. These values lie between 12.8% and 24.4% of the design value of AASHTO (1996) for $\Delta T_{\text{seasonal}}$ (120°F). Therefore, it is reasonable to assume that daily temperature variations in Virginia are not likely to be more than 25% of the maximum expected variation of seasonal temperatures.

3.6.2. Mathematical Representation of Temperature-Induced Displacements

In experimental testing, a function generator is generally used to apply displacement cycles. Most function generators are equipped to produce signals in the form of pulse, triangle, and sine function. More advanced function generators let the user input any

mathematical function through their programming interface. Advanced functions are input through a lengthy process of digitalization.

Temperature-induced displacements could be generated by a function based on temperature recordings at a locality. However, this is not practical because the efforts in obtaining such data, and programming time for such a function, usually do not warrant an ideal representation. A sine function is recommended to represent both the daily and the seasonal displacement cycles.

A sine function has three parameters: a base, a set, and an excitation frequency. Selection of the excitation frequency depends on the specimen being tested and the capacity of the loading system being used. The base defines the reference level of the displacements around which displacements are imposed. The set determines the magnitude of the displacements from the lowest point to the highest point. The base and the set of a sine function are illustrated in Figure 3.5.

Simplifications to the ideal case can be made such that a combination of two sine functions – one for the large and one for the small displacement cycles – can be used. Mathematical representation of the function would be:

$$f(t) = a \sin(At) + b \sin(Bt) \quad (3.2)$$

Where,

t = time during testing,

a = magnitude of seasonal displacements,

A = frequency of seasonal displacements,

b = the magnitude of daily displacements, and

B = frequency of daily displacements.

The small cycles would represent the daily displacement variations while the large cycles would represent the seasonal displacement variations. Such a function might look like the one shown in Figure 3.6. In this figure, the small cycles ($b \sin(Bt)$) ride on the large cycles ($a \sin(At)$).

3.6.3. Proposed Model

The representation of temperature-induced displacements as shown in Figure 3.6 assumes that daily displacements would be the same throughout the year. This is not true because of the facts discussed earlier. However, if a constant value for the daily displacements is selected conservatively, the function as given in Equation 3.2 can be used to model the temperature-induced displacements throughout the year in a simplified and conservative manner. In order to use a function that consists of two sine functions, one would need an advanced function generator.

If an advanced function generator is not available, a less sophisticated, but reasonable and practical displacement pattern, could be adopted. A simplified method, which makes use of the superposition rule, can be employed. Large cycles and small cycles can be imposed independently. Such patterns can be achieved by almost any function generator currently in use and without any programming effort at all. It appears reasonable that daily displacement cycles can be imposed in packs of eight for each year. Each of these eight packs consists of 45 days. This appears to be a good compromise between the practicality and the error introduced. Such a simplified representation of displacements is shown in Figure 3.7.

Application of the proposed method can be done in six steps for a given number of years. As seen in Figure 3.7, displacement range of the cycles between days 46 and 91 is the same as those between days 320 and 365. Similarly, days 91-135 pair with days 270-320, and days 135-180 pair with days 225-270. In total, there are five small cycle groups and one large cycle group for a given period of time. Table 3.1 provides the necessary information to simulate temperature-induced displacement cycles for one year for a displacement range from -0.5 to +0.5 inches.

The base and the set (see Figure 3.5 for description) values in Table 3.1 also serve as non-dimensional multipliers. For instance, for a displacement range from -0.75 to +0.75, the values of the set and the base should be multiplied by 1.5 ($0.75/0.50=1.5$). Moreover, if the simulated time is, say 12 years, the number of cycles is multiplied by 12 such that groups 1 and 2 would have 552 cycles each, and groups 2,3, and 4 would have 1092 cycles each. Finally, group 6 would have 12 cycles.

Table 3.1. Proposed representation of temperature-induced displacement cycles for one year for a maximum expected displacement range from -0.5 to +0.5 inches

Group No	Corresponding days	Base	Set	Number of cycles for one year
1	0-46	-0.375	0.25	46
2	46-91, 320-365	-0.188	0.25	91
3	91-135, 270-320	0.000	0.25	91
4	135-180, 225-270	0.188	0.25	91
5	180-225	0.375	0.25	46
6	seasonal	0.000	1.00	1

The proposed method offers a practical, realistic and conservative displacement pattern that can simulate effects of temperature-induced displacement cycles. The method was used in the experimental program of this study to simulate 75 years of bridge life, and proved practical.

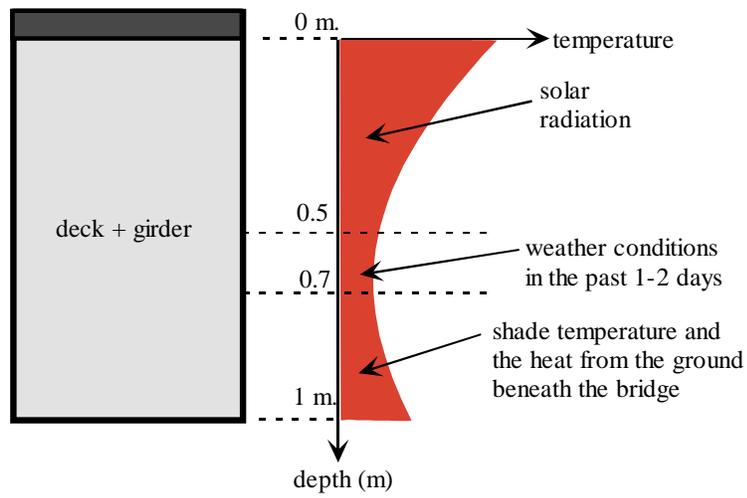
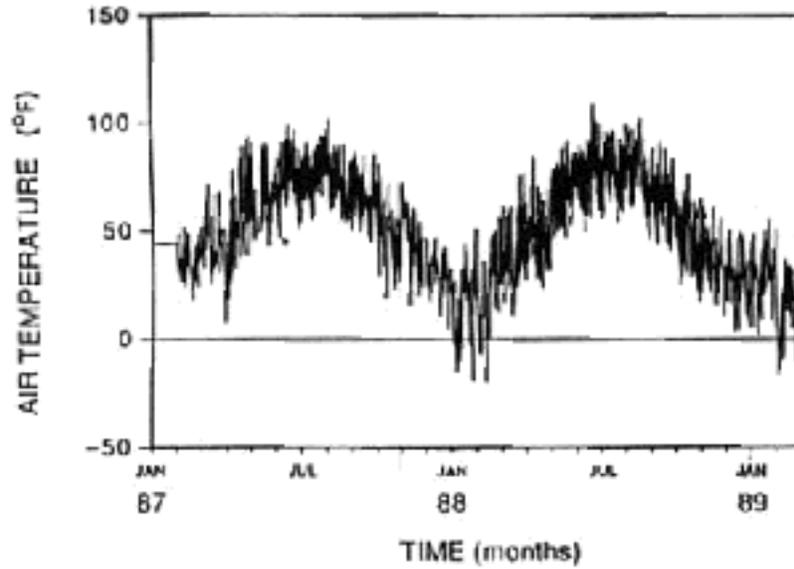
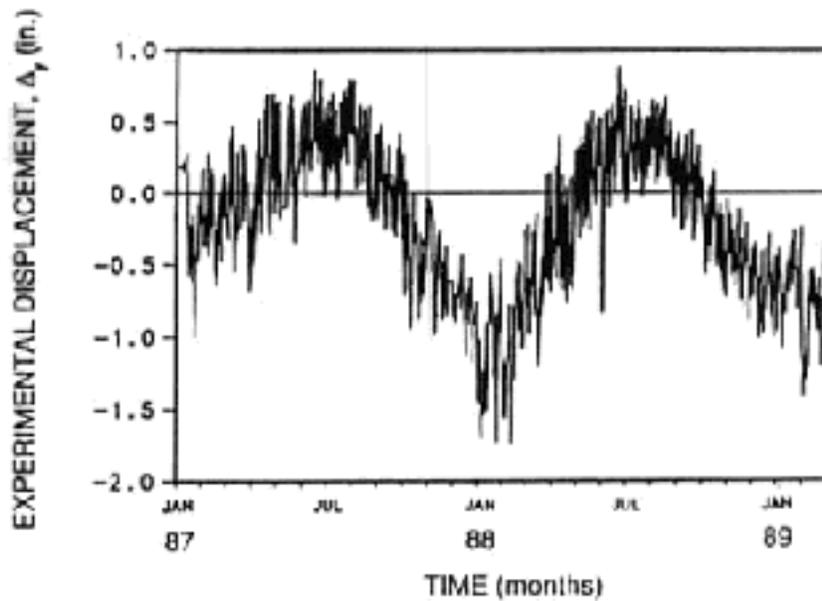


Figure 3.1. Factors controlling temperature distribution over the depth of the superstructure (After Emerson, 1977).



Air Temperature versus Time for Maple River Bridge from January 1987 to February 1989



Experimental Longitudinal Bridge Displacement versus Time for Maple River Bridge from January 1987 to February 1989

Note: 1 inch = 25.4 mm, and $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$

Figure 3.2. Relationship between air temperature and longitudinal bridge displacement for Maple River Bridge (From Girton et al., 1991).

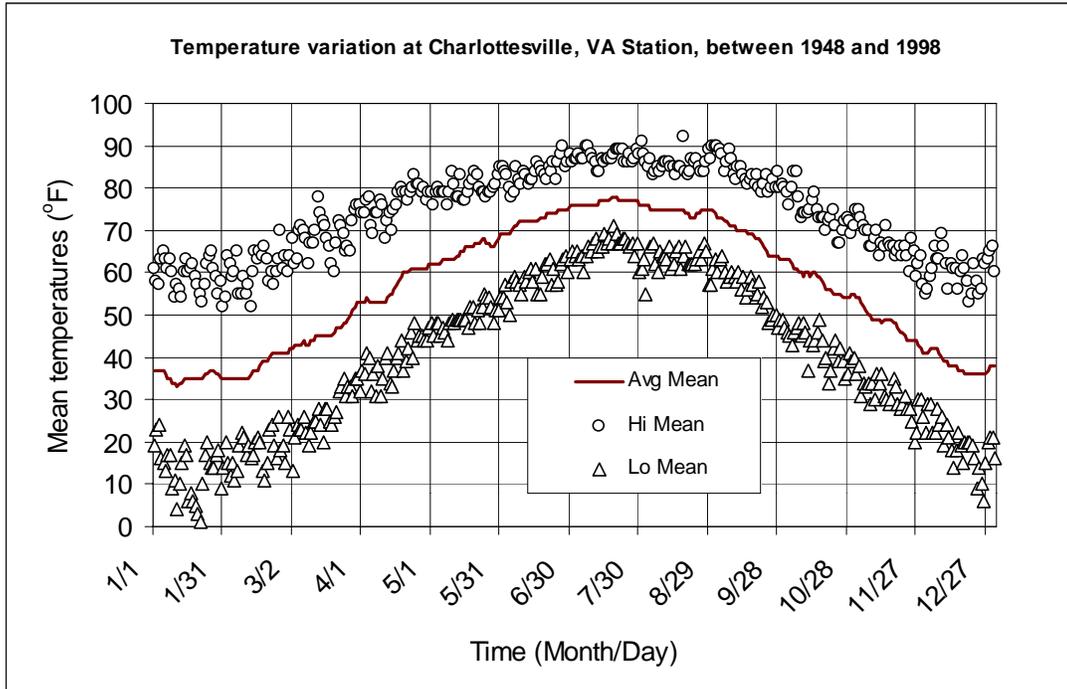


Figure 3.3. Temperature variation in Charlottesville, VA

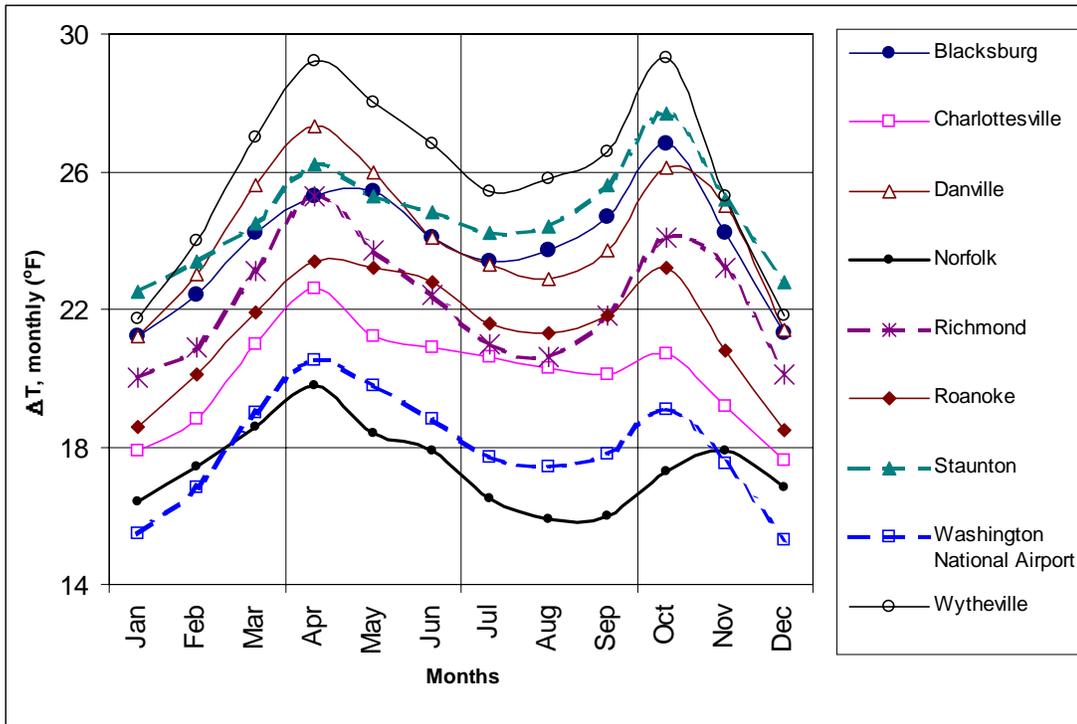


Figure 3.4. Monthly temperature variation in Virginia

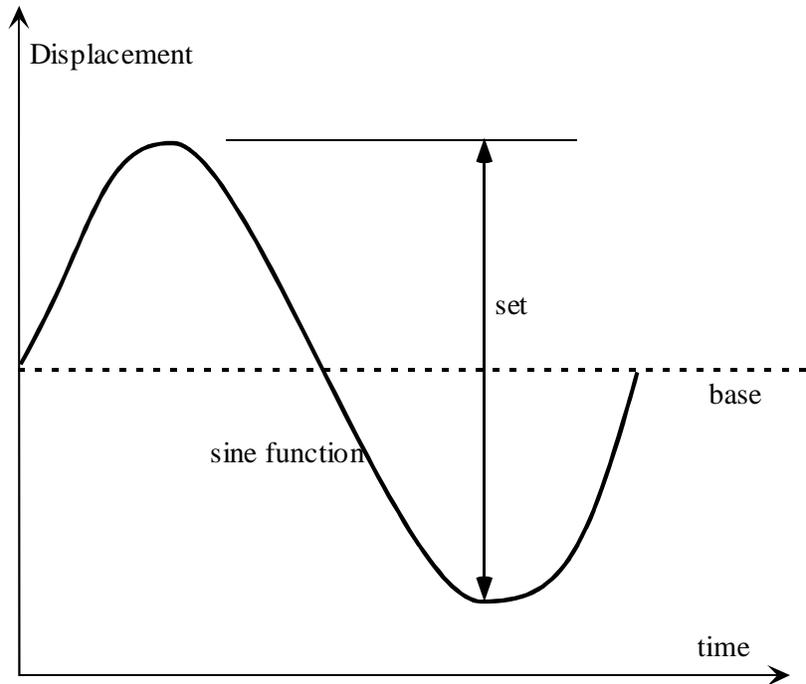


Figure 3.5. Illustration of parameters needed to define a sine function

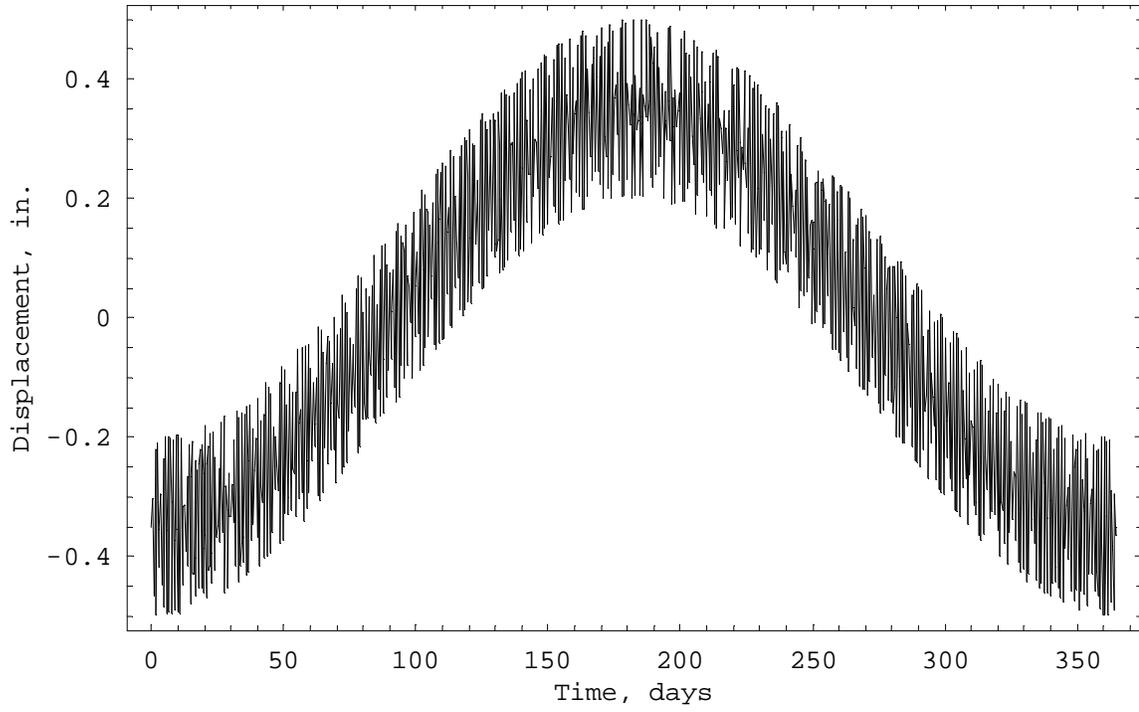


Figure 3.6. Representation of temperature-induced displacements by a combination of two sine-functions

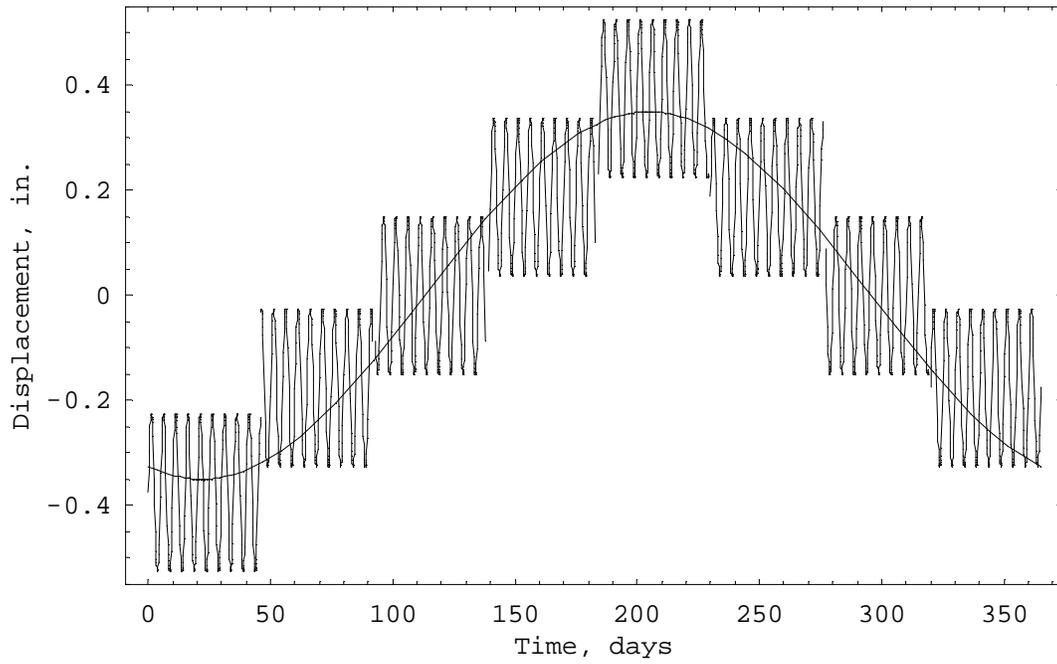


Figure 3.7. Representation of temperature-induced displacements by two separate sine functions