

Causes, Evaluation, and Repair of Cracks in Concrete Structures

Reported by ACI Committee 224



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Causes, Evaluation, and Repair of Cracks in Concrete Structures

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The causes of cracks in concrete structures are summarized. The procedures used to evaluate cracking in concrete and the principal techniques for the repair of cracks are presented. The key methods of crack repair are discussed, and guidance is provided for their proper application.

Keywords: alkali-silica reaction; alkali-carbonate reaction; autogenous healing; concrete; consolidation; corrosion; cracking (fracturing); drying shrinkage; epoxy resins; evaluation; grouting; heat of hydration; mass concrete; methacrylates; mixture proportion; overlay; plastic; polymer; precast concrete; prestressed concrete; reinforced concrete; repair; resins; settlement shrinkage; shrinkage; slab-on-ground; specification; thermal expansion; volume change.

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PREFACE

Cracks in concrete have many causes. They may affect appearance only, or they may indicate significant structural distress or a lack of durability. Cracks may represent the total extent of the damage, or they may point to problems of greater magnitude. Their significance depends on the type of structure, as well as the nature of the cracking. For example, cracks that are acceptable for buildings may not be acceptable in water-retaining structures.

Good crack repair techniques depend on knowing the causes and selecting appropriate repair procedures that take these causes into account; otherwise, the repair may only be temporary. Successful long-term repair procedures must address the causes of the cracks as well as the cracks themselves.

This report is intended to serve as a tool in the process of crack evaluation and repair of concrete structures.

The causes of cracks in concrete are summarized along with the principal procedures used for crack control. Both plastic and hardened concrete are considered. The importance of design, detailing, construction procedures, concrete proportioning, and material properties are discussed.

The techniques and methodology for crack evaluation are described. The need to determine the causes of cracking as a necessary prerequisite to repair is emphasized. The selection of successful repair techniques should consider the causes of cracking, whether the cracks are active or dormant, and the need for repair. Criteria for the selection of crack repair procedures are based on the desired outcome.

Twelve methods of crack repair are presented, including the techniques, advantages and disadvantages, and areas of application for each.

CHAPTER 1—CAUSES AND CONTROL OF CRACKING

1.1—Introduction

This chapter presents a brief summary of the causes of cracks and means for their control. Cracks are categorized as occurring either in plastic concrete or hardened concrete (Kelly 1981; Price 1982). In addition to the information provided herein, further details are presented in ACI 224R and articles by Carlson et al. (1979), Kelly (1981), Price (1982), and Abdun-Nur (1983). Additional references are cited throughout the chapter.

1.2—Cracking of plastic concrete

1.2.1 Plastic shrinkage cracking—When moisture evaporates from the surface of freshly placed concrete faster than it is replaced by bleed water, the surface concrete shrinks. Due to the restraint provided by the concrete below the drying surface layer, tensile stresses develop in the weak, stiffening plastic concrete. This results in shallow cracks of varying depths that may form a random, polygonal pattern, or be essentially parallel to one another (Fig. 1.1). These cracks may be fairly wide (as much as 1/8 in. [3 mm]) at the surface. They range from a few inches to many feet in length, and are spaced from a few inches (millimeters) to as much as 10 ft (3 m) apart. Plastic shrinkage cracks begin as shallow cracks, but can become full-depth cracks later in the life of the concrete.

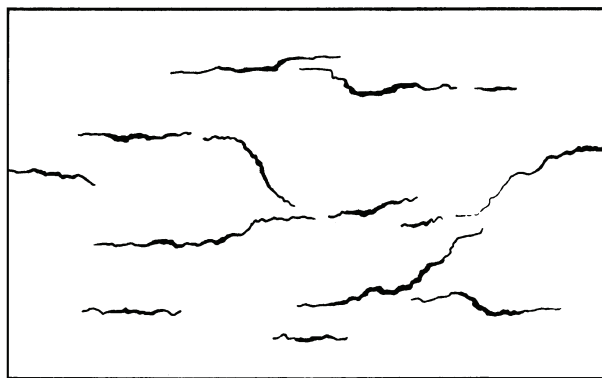


Fig. 1.1—Typical plastic shrinkage cracking (Price 1982).

Plastic shrinkage cracking is usually associated with the rapid loss of moisture caused by a combination of factors that include high air and concrete temperatures, low relative humidity, and high wind velocity at the surface of the concrete. Concrete with lower amounts of bleed water, such as those containing mineral admixtures (especially silica fume) have a greater tendency to undergo plastic shrinkage cracking than concrete with a greater tendency to bleed.

Because plastic shrinkage cracking is due to a differential volume change in the plastic concrete, successful control measures require a reduction in the relative volume change between the surface and other portions of the concrete.

Steps can be taken to prevent rapid moisture loss due to hot weather and dry winds (ACI 224R, 302.1R, and 305R). These measures include the use of fog nozzles to saturate the air above the surface and the use of plastic sheeting to cover the surface between finishing operations. Windbreaks to reduce the wind velocity and sunshades to reduce the surface temperature are also helpful. It is good practice to schedule flatwork after the windbreaks have been erected. During hot, windy weather with low humidity, it is sometimes advisable to reschedule the concrete placement or to initiate concrete operations at night.

1.2.2 Settlement cracking—Concrete has a tendency to continue to consolidate after initial placement, vibration, and finishing. During this period, the plastic concrete may be locally restrained by reinforcing steel, a previous concrete placement, or formwork. This local restraint may result in voids, cracks, or both, adjacent to the restraining element (Fig. 1.2). When associated with reinforcing steel, settlement cracking increases with increasing bar size, increasing slump, and decreasing cover (Dakhil et al. 1975); this is shown in Fig. 1.3 for a limited range of these variables. The degree of settlement cracking may be intensified by insufficient vibration or by the use of leaking or highly flexible forms. Suprenant and Malisch (1999) demonstrated that the addition of fibers can reduce the formation of settlement cracks.

The following items will reduce settlement cracking:

- Form design following ACI 347;
- Concrete vibration (and revibration) (ACI 309R);
- Provision of a time interval between the placement of concrete in columns or deep beams and the placement of concrete in slabs and beams (ACI 309.2R);

- Use of the lowest possible slump;
- An increase in concrete cover; and
- Addition of fibers.

1.3—Cracking of hardened concrete

1.3.1 Drying shrinkage—A common cause of cracking in concrete is restrained drying shrinkage. Drying shrinkage is caused by the loss of moisture from the cement paste constituent, which can shrink by as much as 1%. Fortunately, aggregate particles provide internal restraint that reduces the magnitude of this volume change to about 0.06%. On the other hand, concrete tends to expand when wetted (the volume increase can be the same order of magnitude as that observed due to shrinkage).

These moisture-induced volume changes are a characteristic of concrete. If the shrinkage of concrete could take place without restraint, the concrete would not crack. It is the combination of shrinkage and restraint (provided by another part of the structure, by the subgrade, or by the moist interior of the concrete itself) that causes tensile stresses to develop. When the tensile strength of the material is exceeded, concrete will crack. Cracks may propagate at much lower stresses than are required to cause crack initiation (ACI 446.1R).

In massive concrete elements, tensile stresses are caused by differential shrinkage between the surface and the interior concrete. The higher shrinkage at the surface causes cracks to develop that may, with time, penetrate deeper into the concrete.

The magnitude of the tensile stresses induced by volume change is influenced by a combination of factors, including the amount and rate of shrinkage, the degree of restraint, the modulus of elasticity, and the amount of creep. The amount of drying shrinkage is influenced mainly by the amount and type of aggregate and the cement paste (cement and water) content of the mixture. As the quantity of aggregate increases, the shrinkage decreases (Pickett 1956). The higher the stiffness of the aggregate, the more effective it is in reducing the shrinkage of the concrete; that is, the shrinkage of concrete containing sandstone aggregate may be more than twice that of concrete with granite, basalt, or high-quality limestone (Carlson 1938). The higher the water and cement contents, the greater the amount of drying shrinkage (U.S. Bureau of Reclamation 1975; Schmitt and Darwin 1999; Darwin et al. 2004).

Surface crazing (alligator pattern) on walls and slabs is an example of drying shrinkage on a small scale. Crazing usually occurs when the surface layer of the concrete has a higher water content than the interior concrete. The result is a series of shallow, closely spaced, fine cracks.

A procedure that will help reduce settlement cracking, as well as drying shrinkage in walls, is reducing the water content of the concrete as the wall is placed from the bottom to the top (U.S. Bureau of Reclamation 1975; ACI 304R). Using this procedure, bleed water from the lower portions of the wall will tend to equalize the water content within the wall. To be successful, this procedure needs careful control of the concrete and proper consolidation.

Shrinkage cracking can be controlled by using contraction joints and proper detailing of the reinforcement. Shrinkage

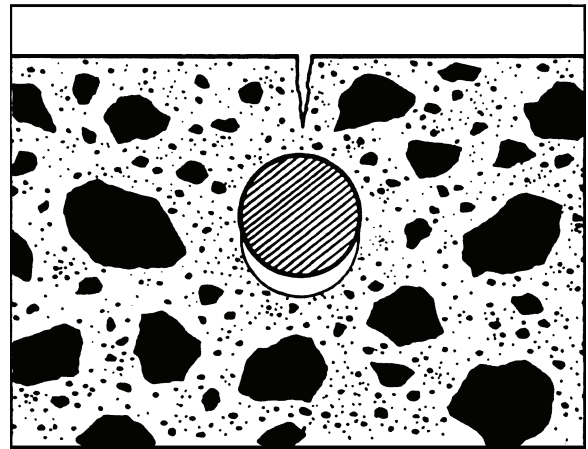


Fig. 1.2—Crack formed due to obstructed settlement (Price 1982).

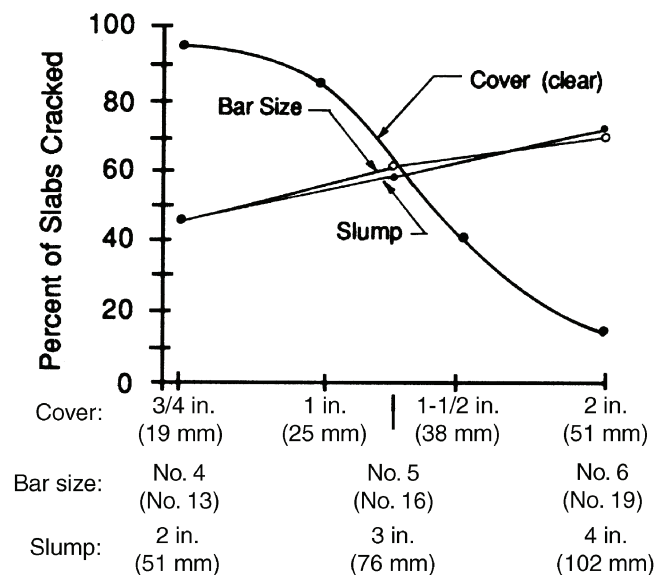


Fig. 1.3—Settlement cracking as a function of bar size, slump, and cover (Dakhil et al. 1975).

cracking may also be reduced or even eliminated by using shrinkage-compensating cement or a shrinkage-compensating admixture. The reduction or elimination of subslab restraint can also be effective in reducing shrinkage cracking in slabs-on-ground (Wimsatt et al. 1987). In cases where crack control is particularly important, the minimum requirements of ACI 318 may not be adequate. These points are discussed in greater detail in ACI 224R, which describes additional construction practices designed to help control the drying shrinkage cracking that does occur, and in ACI 224.3R, which describes the use and function of joints in concrete construction.

Autogenous shrinkage “is a special case of drying shrinkage” (Mindess et al. 2003) that results from self-desiccation (internal drying) in concretes with water-cementitious material ratios (w/cm) below 0.42, but most often observed at a w/cm below 0.30. Thus, it is a problem often associated with high-strength concretes. Autogenous shrinkage occurs without the loss of moisture from the bulk concrete.

The self-desiccation occurs as the relative humidity in interior voids drops to 75 to 80%, which results in bulk shrinkage. Autogenous shrinkage strain is typically about 40 to 100×10^{-6} (Davis 1940), but has been measured as high as 2300×10^{-6} for concrete with a w/cm of 0.20 (Ai 2000). Houk et al. (1969) found that autogenous shrinkage increases with increasing temperature, cement content, and cement fineness.

1.3.2 Thermal stresses—Temperature differences within a concrete structure may be caused by portions of the structure losing heat of hydration at different rates or by the weather conditions cooling or heating one portion of the structure to a different degree or at a different rate than another portion of the structure. These temperature differences result in differential volume changes. When the tensile stresses due to the differential volume changes exceed the tensile strength, concrete will crack. Temperature differentials and the accompanying volume changes due to the dissipation of the heat of hydration of cement are normally associated with mass concrete (which can include large columns, piers, beams, and footings, as well as dams), whereas temperature differentials due to changes in the ambient temperature can affect any structure.

Cracking in mass concrete can result from a greater temperature on the interior than on the exterior. The temperature gradient may be caused by either the center of the concrete heating more than the outside due to the liberation of heat during cement hydration or more rapid cooling of the exterior relative to the interior. Both cases result in tensile stresses on the exterior and, if the tensile strength is exceeded, cracking will occur. The tensile stresses are proportional to the temperature differential, the coefficient of thermal expansion, the effective modulus of elasticity (which is reduced by creep), and the degree of restraint (Dusinberre 1945; Houghton 1972, 1976). The more massive the structure, the greater the potential for temperature differential and restraint.

Procedures to help reduce thermally induced cracking include reducing the maximum internal temperature, delaying the onset of cooling, controlling the rate at which the concrete cools, and increasing the tensile strength of the concrete. These and other methods used to reduce cracking in massive concrete are presented in ACI 207.1R, 207.2R, 207.4R, and 224R.

Hardened concrete has a coefficient of thermal expansion that may range from 3 to $7 \times 10^{-6}/^{\circ}\text{F}$ (6 to $13 \times 10^{-6}/^{\circ}\text{C}$), with a typical value of $5.5 \times 10^{-6}/^{\circ}\text{F}$ ($10 \times 10^{-6}/^{\circ}\text{C}$). When one portion of a structure is subjected to a temperature-induced volume change, the potential for thermally induced cracking exists. Designers should give special consideration to structures in which some portions are exposed to temperature changes, while other portions of the structure are either partially or completely protected. A drop in temperature may result in cracking in the exposed element, whereas increases in temperature may cause cracking in the protected portion of the structure. Temperature gradients cause deflection and rotation in structural members; if restrained, serious stresses can result (Priestley 1978; Hoffman et al. 1983; Haynes

2001; ACI 343R). Allowing for movement by using properly designed contraction and isolation joints and correct detailing will help alleviate these problems.

1.3.3 Chemical reaction—Deleterious chemical reactions may cause cracking of concrete. These reactions may be due to materials used to make the concrete or materials that come into contact with the concrete after it has hardened.

Some general concepts for reducing adverse chemical reactions are presented herein, but only pretesting of the mixture or extended field experience will determine the effectiveness of a specific measure.

Concrete may crack with time as the result of slowly developing expansive reactions between aggregate containing active silica and alkalis derived from cement hydration, admixtures, or external sources (such as curing water, groundwater, deicing chemicals, and alkaline solutions stored or used in the finished structure).

When the alkalis in cement react with susceptible aggregate particles, a reaction rim of alkali-silica gel is formed around the aggregate. If this gel is exposed to moisture, it expands, causing an increase in volume of the concrete mass that will result in cracking and may eventually result in the complete deterioration of the structure. Control measures include using nonreactive aggregates, low-alkali cement, and pozzolans that consist principally of very fine, highly active silica. The first measure may preclude the problem from occurring, while the later two measures have the effect of decreasing the alkali-reactive silica ratio, resulting in the formation of a nonexpanding calcium alkali silicate hydrate.

Certain carbonate rocks participate in reactions with alkalis that, in some instances, produce detrimental expansion and cracking. These detrimental alkali-carbonate reactions are usually associated with argillaceous dolomitic limestones that have a very fine-grained (cryptocrystalline) structure (ACI 201.2R). The affected concrete is characterized by a network pattern of cracks. The reaction is distinguished from the alkali-silica reaction by the general absence of silica gel surface deposits at the crack. The problem may be minimized by avoiding reactive aggregates, dilution with nonreactive aggregates, use of a smaller maximum size aggregate, and use of low-alkali cement (ACI 201.2R).

Sulfates in soil and water are a special durability problem for concrete. When sulfate penetrates hydrated cement paste, it comes in contact with hydrated calcium aluminate. Calcium sulfoaluminate is formed, which may result in an increase in volume. The resulting expansion may cause the development of closely spaced cracks and the eventual deterioration of the concrete. ASTM C 150 Types II and V portland cement, which are low in tricalcium aluminate, will minimize the formation of calcium sulfoaluminate. Sulfate-resistant cements specified in ASTM C 595 and C 1157 are also useful in improving sulfate resistance. Pozzolans that have been tested and shown to impart additional resistance to sulfate attack are beneficial. Using concrete with a low w/cm is important to providing protection against severe sulfate attack.

Detrimental conditions may also occur from the application of deicing salts to the surface of hardened concrete. Damage from deicing chemicals can permeate concrete, reducing the

ability of the concrete protect embedded reinforcement from corrosion. Because corrosion products occupy a greater volume than the original metal, corrosion can lead to delamination and cracking of the concrete. Deicing salts also make concrete more susceptible to freezing-and-thawing damage. To limit these effects, concrete subjected to water-soluble salts should be amply air entrained, have adequate cover of the reinforcing steel, and be made of high-quality, low-permeability concrete.

The effects of these and other problems relating to the durability of concrete are discussed in greater detail in ACI 201.2R.

The calcium silicate hydrate and calcium hydroxide in hydrated cement paste will combine with carbon dioxide in the air to form calcium carbonate. When this occurs, the concrete undergoes irreversible carbonation shrinkage, which may result in surface crazing. In addition, freshly placed concrete surfaces exposed (during the first 24 hours) to carbon dioxide from improperly vented combustion heaters, used to keep concrete warm during the winter months, are susceptible to dusting.

1.3.4 Weathering—The weathering processes that can cause cracking include freezing and thawing, wetting and drying, and heating and cooling. Damage from freezing and thawing is the most common weather-related physical deterioration. Concrete may be damaged by freezing of water in the paste, in the aggregate, or in both (Powers 1975).

Damage in hardened cement paste from freezing is caused by the movement of water to freezing sites and, for water in larger voids, by hydraulic pressure generated by the growth of ice crystals (Powers 1975).

Aggregate particles are surrounded by cement paste, which prevents the rapid escape of water. When the aggregate particles are above a critical degree of saturation, the expansion of the absorbed water during freezing may crack the surrounding cement paste or damage the aggregate itself (Callan 1952; Snowden and Edwards 1962).

Concrete is best protected against freezing and thawing through the use of the lowest practical w/cm and total water content, durable aggregate, and adequate air entrainment. Adequate curing before exposure to freezing conditions is also important. Allowing the structure to dry after curing will enhance its freezing-and-thawing durability.

Other weathering processes that may cause cracking in concrete are alternate wetting and drying, and heating and cooling. Both processes produce volume changes that may cause cracking. If the volume changes are excessive, cracks may occur, as discussed in Sections 1.3.1 and 1.3.2.

1.3.5 Corrosion of reinforcement—Corrosion of a metal is an electrochemical process that requires an oxidizing agent, moisture, and electron flow within the metal; a series of chemical reactions takes place on and adjacent to the surface of the metal (ACI 201.2R and 222R).

The key to protecting metal from corrosion is to stop or reverse the chemical reactions. This may be done by cutting off the supplies of oxygen or moisture or by supplying excess electrons at the anodes to prevent the formation of the metal ions (cathodic protection).

Reinforcing steel usually does not corrode in concrete because a tightly adhering protective oxide coating forms in the highly alkaline environment. This is known as passive protection.

Reinforcing steel may corrode, however, if the alkalinity of the concrete is reduced through carbonation or if the passivity of this steel is destroyed by aggressive ions (usually chlorides). Corrosion of the steel produces iron oxides and hydroxides that have a volume much greater than the volume of the original metallic iron (Bentur et al. 1997). This increase in volume causes high radial bursting stresses around reinforcing bars and results in local radial cracks. These splitting cracks can propagate along the bar, resulting in the formation of longitudinal cracks (parallel to the bar) or spalling of the concrete. A broad crack may also form at a plane of bars parallel to a concrete surface, resulting in delamination, which is a well-known problem in bridge decks.

Cracks provide easy access for oxygen, moisture, and chlorides; thus, minor splitting (longitudinal) cracks can create a condition in which corrosion and cracking are accelerated. Cracks transverse to reinforcement do not usually cause continuing corrosion of the reinforcement if the concrete has low permeability. The exposed portion of a bar at a crack acts as an anode. At early ages, local corrosion occurs; the wider the crack, the greater the corrosion, because a greater portion of the bar has lost its passive protection. For continued corrosion to occur, however, oxygen and moisture must be supplied to other portions of the same bar or bars that are electrically connected by direct contact or through hardware, such as chair supports. If the combination of density and cover thickness is adequate to restrict the flow of oxygen and moisture, then the corrosion process is self-sealing (Verbeck 1975).

Corrosion can continue if a longitudinal crack forms parallel to the reinforcement because passivity is lost at many locations and oxygen and moisture are readily available along the full length of the crack.

Other causes of longitudinal cracking, such as high bond stresses, transverse tension (for example, along stirrups or along slabs with two-way tension), shrinkage, and settlement, can initiate corrosion.

For general concrete construction, the best protection against corrosion-induced splitting is the use of concrete with low permeability and adequate cover. Increased concrete cover over the reinforcement is effective in delaying the corrosion process by limiting carbonation, as well as access by oxygen, moisture, and chlorides, and also in resisting the splitting and spalling caused by corrosion or transverse tension (Gergely 1981; Beeby 1983). In the case of large bars and thick covers, it may be necessary to add small transverse reinforcement (while maintaining the minimum cover requirements) to limit splitting and to reduce the surface crack width (ACI 345R).

In very severe exposure conditions, additional protective measures may be required. A number of options are available, such as coated reinforcement, sealers, or overlays on the concrete, corrosion-inhibiting admixtures, and cathodic protection (Transportation Research Board 1993). Any procedure that effectively prevents access of oxygen and

moisture to the steel surface or reverses the electron flow at the anode will protect the steel. In most cases, concrete must be allowed to breathe; that is, water must be allowed to evaporate from the concrete.

1.3.6 Poor construction practices—A wide variety of poor construction practices can result in cracking in concrete structures. Foremost among these is the common practice of adding water to concrete to increase workability. Added water has the effect of reducing strength, increasing settlement, and increasing drying shrinkage. When accompanied by a higher cement content to help offset the decrease in strength, an increase in water content will also mean an increase in the temperature differential between the interior and exterior portions of the structure, resulting in increased thermal stresses and possible cracking. In addition, by adding cementitious material, even if the w/cm remains constant, more shrinkage will occur because the paste volume is increased.

Lack of curing will increase the degree of cracking within a concrete structure. The early termination of curing will allow for increased shrinkage at a time when the concrete has low strength. The lack of hydration of the cement, due to drying, will result not only in decreased long-term strength, but also in the reduced durability of the structure.

Other construction problems that may cause cracking are inadequate formwork supports, inadequate consolidation, and placement of construction joints at points of high stress. Lack of support for forms or inadequate consolidation can result in settlement and cracking of the concrete before it has developed sufficient strength to support its own weight, while the improper location of construction joints can result in the joints opening at these points of high stress. Methods to prevent cracking due to these and other poor construction procedures are well known (ACI 224R, 224.3R, 302.1R, 304R, 305R, 308R, 309R, 345R, and 347), but require special attention to ensure their proper execution.

1.3.7 Construction overloads—Construction loads can often be more severe than those experienced in service. Unfortunately, these conditions may occur at early ages when the concrete is most susceptible to damage, and they often result in permanent cracks. Precast members, such as beams and panels, are most frequently subject to this abuse, but cast-in-place concrete can also be affected. A common error occurs when precast members are not properly supported during transport and erection. The use of arbitrary or convenient lifting points may cause severe damage. Lifting eyes, pins, and other attachments should be detailed or approved by the designer. When lifting pins are impractical, access to the bottom of a member must be provided so that a strap may be used. The PCI Committee on Quality Control Performance Criteria (1983, 1985) provides additional information on the causes, prevention, and repair of cracking related to fabrication and shipment of precast or prestressed beams, columns, hollow core slabs, and double tees.

Operators of lifting devices should exercise caution and be aware that damage may be caused even when the proper lifting accessories are used. A large beam or panel lowered too fast and stopped suddenly results in an impact load that may be several times the dead weight of the member.

Another common construction error that should be avoided is prying up one corner of a panel to lift it off its bed or break it loose.

When considering the support of a member for shipment, the designer should be aware of loads that may be induced during transportation. Some examples that occur during shipment of large precast members via tractor and trailer are jumping curbs or tight highway corners, torsion due to differing roadway super-elevations between the trailer and the tractor, and differential acceleration of the trailer and the tractor.

Pretensioned beams can present unique cracking problems at the time of stress release—usually when the beams are less than 1 day old. Multiple strands should be detensioned following a specific pattern so as not to place unacceptable eccentric loads on the member. If all of the strands on one side of the beam are released while the strands on the other side are still stressed, cracking may occur on the side with the unreleased strands. These cracks are undesirable, but should close with the release of the balance of the strands.

In the case of a T-beam with a heavily reinforced flange and a highly prestressed thin web, cracks may develop at the web-flange junction.

Another practice that can result in cracks near beam ends is tack welding embedded bearing plates to the casting bed to hold them in place during concrete placement. The tack welds are broken only after enough prestress is induced during stress transfer to break them. Until then, the bottom of the beam is restrained while the rest of the beam is compressed. Cracks will form near the bearing plates if the welds are too strong.

Thermal shock can cause cracking of steam-cured concrete if it is treated improperly. The maximum rate of cooling frequently used is 70 °F (40 °C) per hour (ACI 517.2R; Verbeck 1958; Shideler and Toennies 1963; Kirkbride 1971b). When brittle aggregate is used and the strain capacity is low, the rate of cooling should be decreased. Even following this practice, thermally induced cracking often occurs. Temperature restrictions should apply to the entire beam, not just locations where temperatures are monitored. If the protective tarps used to contain the heat are pulled back for access to the beam ends when cutting the strands, and if the ambient temperatures are low, thermal shock may occur. Temperature recorders are seldom located in these critical areas.

Similar conditions and cracking potential exist with precast blocks, curbs, and window panels when a rapid surface temperature drop occurs.

It is believed by many (ACI 517.2R; Mansfield 1948; Nurse 1949; Higginson 1961; Jastrzebski 1961; Butt et al. 1969; Kirkbride 1971a; Concrete Institute of Australia 1972; PCI Energy Committee 1981) that rapid cooling may cause cracking only in the surface layers of very thick units and that rapid cooling is not detrimental to the strength or durability of standard precast products (PCI Energy Committee 1981). One exception is transverse cracking observed in pretensioned beams subjected to cooling before detensioning. For this reason, pretensioned members should be