EXPANSION AND CONTRACTION JOINTS IN REINFORCED CONCRETE BUILDINGS

An Annotated Bibliography
1907 - 1984

by

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INTRODUCTION

The majority of the existing literature concerning expansion and contraction joints in reinforced concrete buildings is limited to general, common sense information on joint location and rules of thumb on joint spacing. Often, these recommendations are offered without any background as to how they were determined, or complete explanation as to their use.

The need for a review of expansion and contraction joint spacing and location design practices is apparent based on the confusion which surrounds this topic for most practicing engineers. A major source of this confusion is the varied, and, at times, contradictory recommendations found in the literature. The changes which have occurred and are continuing in the field of reinforced concrete design compound the need for a review.

The purpose of this bibliography is to collect the available information concerning expansion joints and contraction joints in reinforced concrete buildings. In this introduction, emphasis is placed on the presentation of the more rational methods of expansion and contraction joint design, as opposed to rule of thumb guidelines.

Most of the rule of thumb guidelines used for the spacing and location of expansion and contraction joints have been around for more than forty years. They were developed by engineers who observed crack locations in existing structures and then placed a joint at those locations in subsequent structures. This is a common sense approach, but to continue to use these spacing guidelines blindly on today's structures is neither reasonable nor appropriate in all cases.

The structures built today are very different from the structures built forty years ago. There have been many advances in building and material technology. The higher strength materials available today, combined with an increased understanding of structural behavior have led to higher allowable stresses. Structures are now generally proportioned using strength design rather than working stress design. Margins of safety have been reduced, reflecting an increased confidence in the materials, their behavior, and the analysis techniques. As a result, today's buildings are more flexible due to smaller, more efficient members.

But as the safety margins have been reduced so also have the margins which are available to withstand the "secondary" stresses caused by creep, shrinkage, and temperature variations. These stresses have been largely ignored in the past due to the complex calculations required and the saving grace of the larger safety margins. However, these stresses may no longer be secondary and are often the primary considerations.

The ACI Building Code, ACI 318-83, states that "consideration shall be given to the effects of forces due to ... shrinkage and temperature." In all but a few special cases, such as nuclear containments, this consideration commonly consists of checking the building length against a chart or one of the rules of thumb to determine if it requires an expansion joint. Contraction or partial-contraction joints are then placed based on yet another rule of thumb. Often the final decision of whether to use an expansion or a contraction joint comes down to someone's opinion.

Contraction and expansion joint location and design appear to be gaps in the current research on controlling the effects of creep, shrinkage, and temperature change, and the prevention of cracking in reinforced concrete buildings. Today it is a subject that is little understood and largely ignored.

The need for a more rational method to determine joint locations is commonly expressed in the literature. In the past, to minimize cracking in their structures, individual designers had to learn what joint spacings would work for their structures and for their particular locales. It was a trial and error procedure, with every designer learning from his own mistakes as he tried to adapt the prevailing rules of thumb to match his structure's specific conditions and location.

Contraction joint spacing was investigated by Vetter in 1933. He developed a rational analysis, based on the bond stress between the reinforcement and the concrete, to determine the stress in a continuous reinforced concrete wall due to variations in moisture content and temperature. As a result of this work, he was able to calculate the distance at which cracks would occur for a given percent of reinforcement. Vetter noted that while all cracking could not be eliminated, large cracks could be replaced with many small, non-detrimental cracks.

This method of analysis and design was used to develop the current approach for the spacing of contraction joints in sanitary engineering structures. In ACI 350R-83, "Concrete for Sanitary Engineering Structures," Vetter's method was used to produce a chart which specifies the percentage of shrinkage and temperature reinforcement for a given contraction joint spacing. This is one of the major improvements in the new version of the ACI 350 report.

The rule of thumb guidelines for contraction joint spacing have worked reasonably well in the past for typical structures. By applying these guidelines in a conservative manner, the designer could be reasonably assured that the structure would not experience major detrimental cracking due to contraction. The new ACI 350 report, however, now gives the designer more flexibility. Contraction joints can now be spaced appropriately for the percent of shrinkage and temperature reinforcement used.

This same approach could well be applied to non-sanitary engineering structures. However, it should be noted that the "sanitary durability coefficients" reduce the service load stresses in the walls of sanitary engineering structures below the values obtained if the structure were designed by ACI 318-83 alone. Some adjustment in the chart used in ACI 350R-83 would be required.

A rational solution for the determination of expansion joint spacings has proved to be more elusive. The first attempt at a rational solution was not made until the 1970's. Five references present rational methods for determining expansion joint spacing. Except for two references which use the same method, each paper approaches the problem somewhat differently, and unfortunately, yield no less disparate results than the rule of thumb dimensions they attempt to replace.

The first method was developed by Martin and Acosta in 1970 for one-story reinforced concrete frame structures. They analyzed these structures for an uniform temperature change equal to two-thirds of the difference between normal daily maximum and minimum temperatures plus an equivalent temperature drop of 30°F (17 C) to account for drying shrinkage. They found that the critical moments occur in the exterior columns and beams. Using ACI 318-63 as guidance, they determined that the shrinkage and temperature forces should not exceed twenty percent of the dead load plus forty percent of the live load to properly be neglected in structural computations. From this criterion, an equation was developed for the maximum expansion joint spacing.

In 1971, a second approach was presented by Hendry and Nourini. This method uses a strength of materials formulation to determine the tensile stress resulting from a change in mean temperature between roof slabs and concrete bearing walls. This formulation yields a "critical fissure length," the length of slab or wall, from the point of zero stress, required to develop a stress high enough to cause tensile cracking. The recommended distance between expansion joints is twice this value.

The next approach was developed by the National Academy of Sciences in 1974. Their research consisted of a review of the current methods used by federal agencies to determine expansion joint spacing in federal buildings, an analysis of an unpublished report on temperature change and horizontal movements in nine federal buildings, and a two-dimensional elastic frame analyses on typical multi-story buildings. The study committee developed a chart, used with several modifying factors, which gives the recommended expansion joint spacing based on the material of construction and the expected yearly temperature range that the building will see in service.

The fourth method for determining expansion joint spacing was published in 1978 by Varyani and Radhaji. They used moment distribution to analyze typical multi-story frames for a uniform temperature change. The maximum fall in temperature used in their analysis was taken to be two-thirds the difference between maximum and minimum daily temperature plus $15^{o}C$ (27 F), to account for drying shrinkage. Based on the strength of the critical sections, located at the exterior columns and beams, they determined the maximum structure length for which no additional reinforcement would be required beyond that for normal loading. This length was the recommended expansion joint spacing.

The most recent publication to offer a method for the location and spacing of expansion joints was issued by the Portland Cement Association in 1982. The PCA recommends that the need for expansion joints first be determined empirically using the method developed by the National Academy of Sciences in 1974, and then "if the results are not sufficiently comprehensive to be applicable to the type of structure being studied, a more precise analysis should be undertaken." Other than providing a list of the factors to be considered in this more precise analysis, no specific procedures are described.

The methods proposed for expansion joint location and spacing do not appear to be as complete or as comprehensive as Vetter's method for contraction joint spacing.

The problem of contraction joint spacing is a material problem, primarily governed by the low tensile strength of concrete and the bond stress between reinforcing steel and concrete. The solution developed by Vetter takes into account all of the major factors that affect contraction joint spacing, and appears to be both practical and conservative.

A solution for the location and spacing of expansion joints, however, must consider the structure as a whole. A great many more factors must be considered to arrive at a rational solution. Some of the considerations which should be included are the size and shape of the building, the type of construction, the connection to the foundation, the location or climate, the size of the structural members, the construction procedures, the heating and/or air conditioning provided, and the insulation of the building.

Each of the expansion joint design methods either deals with only one specific type of structural arrangement or with only one criteria of performance, i.e., either crack control or strength. None of the methods appear to adequately deal with both of these factors.

The solution methods developed by Martin and Acosta and by Varyani and Radhaji are both solely concerned with the strength of the structure. These methods determine the forces due to shrinkage and temperature and then calculate the expansion joint spacing so that these forces can properly be neglected. If one could have confidence in the results, use of either of these methods would satisfy the requirement stated of ACI 318-83 to consider the forces due to the effects of shrinkage and temperature. Neither of these methods, however, addresses the subject of crack control.

The solution method developed by Hendry and Nourini is primarily based on crack control. This method, however, is only applicable to bearing wall structures.

The procedure developed by the National Academy of Sciences was based on a study of the performance of nine federal buildings over the period of one year, a set of computer analyses of similar buildings, and a chart adapted from one federal agency's expansion joint criteria. The limits on expansion joint spacing used on this chart are not rationalized other than to explain that they are "assumed to reflect the considered consensus of long experience within the engineering profession." This procedure, while addressing many of the factors that relate to expansion joint spacing, is based on a limited amount of field data and handles these factors in a general manner.

A complete solution for the location and spacing of expansion joints must consider both strength and serviceability. It should limit both the forces due to shrinkage and temperature change, and the degree of detrimental cracking due to these forces. This requires that contraction joint location and spacing as well as expansion joint location and spacing be considered in the same analysis.

The methods described for the spacing of expansion joints yield solutions that are as varied and inconsistent as the rules of thumb they are attempting to replace. It is not surprising that the methods described give such varying results. In addition to approaching the problem differently, there is very little field data available to improve analysis techniques or to verify existing methods. Only a few structures have been instrumented to measure shrinkage, moisture or thermal movements. Repair work on existing structures has seldom been documented in the past, and cause and effect relationships are often left undetermined.

Current trends in construction require a greater understanding of expansion joints. Ever larger buildings are being constructed, usually with some attempt to control drying shrinkage. The use of shrinkage-compensating concrete is also becoming more prevalent. In structures made with shrinkage-compensating concrete contraction joints are not used.

In general, the trend is to avoid the use of expansion joints in buildings wherever possible. Economics has been the major reason. Both the initial cost of the joint itself, i.e, the necessity for additional structural members, and the long-term anticipated maintenance and repair costs are used to argue that expansion joints are too expensive and are best left out of a structure. Current trends in construction indicate, however, that when expansion joints are used, they will be placed at greater spacing and must accommodate larger movements.

To fully utilize the advances that have been made in concrete construction technology, a better understanding of expansion joints and the relation between expansion and contraction joints are needed. To increase our understanding of expansion and contraction joints, many more field investigations of the response of existing buildings to shrinkage and temperature changes are required. These are needed, both to verify and refine the methods of location and spacing available now, and to provide the data necessary for future design procedures. Opinions currently differ as to what temperature differential is significant and should be used for design. This critical factor cannot be resolved until further testing determines the relationship between ambient temperatures and the temperature of the structural members within a building.

For now, the designer must still rely on engineering judgment. While contraction joints can be located and spaced rationally, with an assured degree of conservatism, expansion joints cannot. The best a designer can do is to try to match the structure with a complimentary solution method and then evaluate the results with knowledge of the uncertainties inherent in the analysis.

GLOSSARY

One of the major sources of confusion in the literature is the terminology used to describe the various types of joints. Historically, the terms contraction joint and expansion joint have often been used interchangeably to mean any joint where stresses due to volume changes are relieved. In this bibliography, these terms have different, specific meanings, as described below.

The use of the term 'control joint' is found in much of the literature. Use of this term is discouraged due to its vagueness, since it is not clear what is being controlled.

In this bibliography, every attempt has been made to use correct terminology. In a reference, if a joint was described incorrectly, the correct term is substituted in the annotation.

CONSTRUCTION JOINT* - The surface where two successive placements of concrete meet, across which it is desirable to develop and maintain bond between the two concrete placements, and through which any reinforcement which may be present is not interrupted.

CONTRACTION JOINT* - Formed, sawed, or tooled groove in a concrete structure to create a weakened plane and regulate the location of cracking resulting from the dimensional change of different parts of the structure.

CONTROL JOINT - Obsolete term, usually used to mean a contraction joint or a partial contraction joint, but also occasionally used to mean an expansion joint. Use of this term is to be discouraged.

EXPANSION JOINT* - A separation between adjoining parts of a concrete structure which is provided to allow small relative movements such as those caused by thermal changes to occur independently.

ISOLATION JOINT* - A separation between adjoining parts of a concrete structure, usually a vertical plane, at a designed location such as to interfere least with the performance of the structure, yet such as to allow relative movement and avoid formation of cracks elsewhere in the concrete and through which all or part of the bonded reinforcement is interrupted.

PARTIAL CONTRACTION JOINT - A contraction joint where a portion of the normal longitudinal reinforcement is continued through the joint.

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* ACI Committee 116, "Cement and Concrete Terminology (ACI 116R-78)," ACI Manual of Concrete Practice, Parts 1 and 2, American Concrete Institute, Detroit, 1984.

The following bibliography is arranged in chronological order by year. Then within each year the entries are made alphabetically.

Since the purpose of this bibliography is to assemble references containing information concerning expansion and contraction joints in concrete buildings, these summaries have been written not only to describe the reference in general, but to clearly show what pertinent information they contain.

1907

1. Bellinger, L.F., "Expansion Joints in Concrete Structures with Special Reference to Block Construction in Drydocks and Reservoirs," Engineering News, V. 57, No. 18, 2 May 1907, pp. 472-475.

Thermal and shrinkage effects on concrete are discussed. Two methods to deal with the phenomenon are proposed. The first method is to not provide any joints, but to calculate the percent reinforcement needed to carry the additional stress due to the expansion or contraction of the structure. Due to the large reinforcing ratios obtained, the author believes this approach is not practical.

The second method is to break up the structure into smaller separate units, and provide sufficient reinforcement for these smaller length units. Expansion joints are placed at the separations. This is the procedure recommended by the author.

Although the author makes no specific recommendations as to the distance between these separations, he discusses numerous examples of reservoirs and drydocks where different spacings have been used and evaluates their performance.

There is also a discussion of "block" construction and its use in constructing drydocks. With block construction, a structure is poured in separate blocks to allow shrinkage to take place prior to placement of the next block.

2. Editorial, "Expansion and Contraction in Concrete Structures," Engineering News, V. 57, No. 19, 9 May 1907, pp. 513-514.

This editorial discusses the debate over the need for measures to control expansion and contraction in concrete structures. It quotes several representative statements which argue that this concern is simply a fictitious or academic problem and that the designer has no need to consider these effects.

The article urges concern for these subjects by engineers, and points to several articles which seem to demonstrate both the magnitude of the problem and possible solutions. The two solutions discussed are to provide sufficient reinforcement to control the shrinkage and temperature stresses without the use of joints, or to place expansion joints at approximately the distance at which cracking has been observed in existing structures. No mention is made of contraction joints.

The editorial urges research into this problem due to the lack of any quantitative data available.

3. Lewerenz, A.C., "Notes on Expansion and Contraction of Concrete Structures," Engineering News, V. 57, No. 19, 9 May 1907, pp. 512-514.

This article presents observations of the effects of expansion and contraction in reinforced and non-reinforced concrete retaining walls and in drydocks at the naval yard in Puget Sound.

The author inspected several structures of varying construction. A plain concrete retaining wall was found to have numerous cracks on the outside surface of the wall and 3/16th of an inch openings at the expansion joints. In a reinforced concrete retaining wall that had no expansion joints, it was discovered that there were cracks on the outside surface spaced at regular intervals of 75 feet. Inspection of a drydock structure, constructed of reinforced concrete with expansion joints provided at 100 foot intervals, revealed no cracking of importance. No mention is made of contraction joints.

The conclusion presented is that properly reinforced concrete structures with adequate expansion joints can prevent major cracking. It is noted, however, that random surface cracking caused by sudden changes in temperature or because of natural shrinkage of the concrete will not be alleviated by these measures.

1924

4. Pearce, Langdon, "Report of Committee E-8, Expansion Joints in Concrete Construction," ACI Journal, Proceedings, V. 20, 1924, pp. 619-632.

This report summarizes the need for and presents common details of expansion joints used in concrete structures. It was presented to encourage discussion among the membership in hopes that a better understanding of the problem and that better details could be developed.

After briefly discussing the nature of concrete and the reasons why expansion joints are required, the report handles in detail the selection of filler materials and sheet metal barriers. The author presents a classification system for expansion joints based on the service of the joint; whether it shall retain water, pressurized water, rain, or air.

1925

5. Leffler, R.R., "Report of the Committee E-8, Expansion Joints in Concrete Construction, Addendum," ACI Journal, Proceedings, V. 21, 1925, pp. 321-327.

This addendum to the report of the committee E-8 presents several more expansion joint details. There are details for concrete pipe under internal pressure, and other typical pipe joints. A detail for expansion joints in basements floors is also presented.

1933

6. Vetter, C.P., "Stresses in Reinforced Concrete Due to Volume Changes," Transactions, ASCE, V. 98, 1933, pp. 1039-1053.

This paper presents a rational analysis of the stresses which occur in a continuously reinforced concrete wall due to linear expansions or contractions caused by variations in moisture content or temperature. Equations are developed which give the stresses in the reinforcement and the concrete due to these volume changes.

Formulae are given which determine the required reinforcement to prevent major cracking for any combination or degree of moisture or temperature change.

The author demonstrates mathematically that reinforcement cannot prevent shrinkage cracks, but notes that proper reinforcement will cause the formation of many small cracks instead of a single large detrimental crack. He states that one of the results of this investigation should, hopefully, be an increased use of definite contraction joints.

1934

7. Fairchild, L.F., "Concrete in Factory Construction," ACI Journal, Proceedings, V. 31, No. 2,November-December, 1934, pp. 149-164.

This paper is an historical account of the use of concrete in factory construction at the Eastman Kodak Company in Rochester, New York. Reinforced concrete was first used at Kodak in 1898. Since that time 102 major buildings have been erected using reinforced concrete in the structural frame. This has provided the author with a wealth of information concerning the performance of reinforced concrete in factory buildings. He documents, first-hand, the discovery of unexpected problems and the solutions developed to alleviate those problems.

Some of the developments discussed include an appreciation for providing proper cover over the reinforcement, usage of dense concrete at exposed walls to prevent absorption, use of high early strength cement, and use of specialized aggregates for floor finishes.

There is a discussion of concrete spalling from the bottom of beams It was discovered that the reinforcement was too closely spaced to allow coarse aggregate below the bars.

In one structure, an expansion joint system failed. This system consisted of girders resting on column brackets. It was determined that steel sliding surfaces were required to make the system work properly. The system that failed was simply concrete bearing on concrete, presumably with a bond breaker. The author notes that based on their experiences, the preferred procedure is to provide two independent columns about two inches apart, rather than using the girder-bracket system.

1936

8. Gerber, Carl B., "Expansion-Joint Action in a Concrete Balcony," Engineering News Record, V. 116, No. 7,February 13, 1936, pp. 251-252.

During the construction of a reinforced concrete stadium in Fort Myer, Va., special benchmarks were placed at the structure's expansion joints. These allowed joint movements to be measured. Concrete and ambient air temperature readings were also taken. The period of the investigation was from August to December, 1935.

The results were presented in a graphical form. The movement at the expansion joints correspond in a general manner with the temperature readings taken.

The author concludes that because of the magnitude of the movements, excessive tensile stresses would have caused cracking of the concrete if the structure had been restrained. This justifies the expense and the use of the expansion joints.

1943

9. Judd, Samuel, "Bureau of Reclamation Practice of Joints for Concrete Buildings," ACI Journal, Proceedings, V. 39, No. 10, June 1943, pp. 557-563.

This paper describes the methods used by the Bureau of Reclamation to locate, design and construct joints in concrete buildings. The Bureau classifies joints into 4 principal types, construction, contraction, expansion, and partial contraction joints. It is noted that one joint can serve as a combination of types.

Buildings designed by the Bureau are provided with joints between large power units, at large changes in cross section, at changes in building plan, where a building is weakened by openings, and at changes in the type of foundation.

Details are included for several types of standard joints in use by the Bureau of Reclamation.

10. Merrill, W.S., "Prevention and Control of Cracking in Reinforced Concrete Buildings," Engineering News Record, V. 131, No. 23, December 16, 1943, pp. 91-93.

This author describes how, because of a shortage in steel, his company has increasingly turned to reinforced concrete for power plant buildings. This has produced concrete walls of large areas and a need to control unsightly cracking in those walls.

To control the location of cracks, the author describes the use of contraction joints. These are predetermined crack locations, formed by placing a narrow groove on each face of the wall and stopping or cutting 1/2 of the horizontal reinforcement at this point. Several details are presented.

No exact rules of location for these joints can be given. Each job must be studied individually to determine where joints should be made taking into account the structural requirements. To be effective, control joints should be spaced not more than 20 feet apart in walls with frequent openings, and never more than 25 feet apart in solid walls.

The effectiveness of the contraction joints used by the author is increased if the walls and columns are placed so that various sections can shrink individually before the adjacent concrete is placed.

1949

11. Expansion Joints in Concrete Buildings, Concrete Information Pamphlet No. AC-12, Portland Cement Association, June 1949, 4 pp.

This informational pamphlet, one of a series from the Portland Cement Association, discusses the need to consider expansion joints in concrete buildings. Most buildings do not require expansion joints and no definite rules exist to determine those which do. All buildings, however, experience volumetric changes due to initial shrinkage and due to subsequent variations in moisture content and temperature. These volumetric changes can result in detrimental cracking, and possibly a reduction in strength or an impairment in the serviceability of the structure. To properly consider these effects, expansion joints should be investigated early in a building's design.

Several rules of thumb are given to decide when an expansion joint should be provided. It is noted that buildings under 200 feet in length seldom are provided with expansion joints. In longer buildings, it is recommended that they should not be spaced farther apart than 200 feet. In addition, expansion joints should be placed at any weakened section, or abrupt change in section or plan.

Consideration is given to the architectural treatment and requirements concerning expansion joints. Several architectural details are given. The engineer is reminded that the expansion joint should always be as simple as possible without sacrificing effectiveness.

1953

12. Green, Cecil V., "Practical Considerations in the Design and Construction of Concrete Structures for Waterworks," Journal of the Institution of Water Engineers, V. 7, No. 6, October 1953, pp. 465-496.

In this paper, the author addresses the special problems involved in the design and construction of water retaining structures, principally reinforced concrete reservoirs.

While discussing the history of the use of reinforced concrete for these structures, the differences between water retaining and normal concrete structures are said to be not generally understood.

However, an appreciation of the differences can be seen in the particular attention paid to such matters as expansion joints, under-drainage, waterproof linings, and use of lowered allowable concrete stresses to minimize cracking.

The author discusses the materials, the concrete mix, and the handling and placement techniques required to give a dense impermeable concrete.

Considerable discussion is presented concerning the proper design of expansion and contraction joints. The author uses these terms interchangeably to mean a joint where either expansion or contraction is relieved. The author notes, however, that since these structures are normally buried, the principal concern usually is contraction. Contraction joints are suggested to be placed at 25 to 30 feet intervals in the walls of these water retaining structures.

Construction joints are said to be a necessary evil, and it is recommended that they be plainly shown on the drawings.

Numerous joint details used by the author are presented and their performance discussed.

In the discussion which follows this article there is a debate over the use of partial contraction joints. The author is of the opinion that a partial contraction joint would lead to rebar corrosion at the joint. He does not recommend their usage.

13. Hunter, L.E., "Construction and Expansion Joints for Concrete," Civil Engineering and Public Works Review, V. 48, No. 560, February 1953, pp. 157-158, and V. 48, No. 561, March 1953, pp. 263-265.

The author presents a detailed discussion of construction and expansion joints in concrete buildings including the details of construction. He notes that joints in concrete are required because the natural shrinkage of concrete is about 5/8 inch in 100 feet and this would cause cracking if restrained.

For floor construction, the author describes a chessboard, or alternate bay construction principal, in which sections of the floor are cast in units of 15 by 30 feet, or slightly more. After two days, the adjacent sections are cast. He presents construction details for joints in floors.

Buildings of considerable area require expansion joints. He notes the varying opinions as to their placement, and then gives his own guidelines.

In floors, the maximum length between expansion joints is generally 80 feet. In reservoir or roof slabs, because of their exposure, the expansion joint spacing should not exceed 30 to 40 feet. If adequate insulation is provided, however, a spacing of 80 to 100 feet is possible. For basement slabs an optimum expansion joint spacing is 100 feet.

Numerous expansion joint details are included.

14. Rensaa, E.M., "The Cracking Problem in Reinforced Concrete Buildings," The Engineering Journal (Canada), V. 36, November 1953, pp. 1429-1434.

The practice of using joints and hinges simply for the purpose of making stress calculations easier is described as generally a bad practice. The excessive use of expansion joints adds to the cost of construction and maintenance, as well as weakening the structure. The author describes how many engineers use these joints as "ignorance joints."

In discussing the causes and cures of cracking in concrete buildings, the author argues that once the causes are understood, a building can be designed in a more rational manner. Several examples are presented where contraction joints were omitted and the cracking was controlled through the use of expansion joints and additional reinforcement.

Expansion joint locations are recommended for changes in building plan. The author makes no other recommendations for joint location and presents no specific approach to determine their proper spacing.

1954

15. Alcock, R.G., "Repairs to a Fractured Expansion Joint in a 10 M.G. Service Reservoir," Journal of the Institution of Water Engineers (London), V. 8, No. 5, August 1954, pp. 429-437.

This article is a description of the investigation and subsequent repair of a fractured expansion joint that caused severe leakage into an underground water storage reservoir.

The joint is described as a keyed type joint with its adjoining faces painted with bitumen to make them discontinuous. At the center of the keyway a lead sheet was placed to serve as a waterstop. The location was in the wall near the reservoir outlet structure.

The concrete cracked at the base of the keyway allowing water to bypass the waterstop.

16. Kleinlogel, Adolf, Bewegungfugen (Expansion Joints), 5th Edition, W. Ernst & Sohn, Berlin, 1954, 271 pp.

This book thoroughly covers the subject of expansion joints in concrete and reinforced concrete construction. Numerous details and examples of expansion joints in different constructions are given.

The following types of structures are discussed; superstructures, roof construction, silos, liquid retaining tanks and swimming pools, retaining walls and seawalls, locks, harbor construction, unloading docks, concrete pipes, open canals, sanitary structures, smokestacks, concrete bridges, aquaducts, tunnels and mining, concrete roads, and airport runways and taxiways.

In German.

1957

17. Feld, Jacob, "Failures of Concrete Structures," ACI Journal, Proceedings, V. 54, No. 6, December 1957, pp. 449-470.

This survey of significant failures in concrete structures was prepared because of the author's belief that the engineering profession has a duty to discover the causes and cures of such failures. Concrete failures are discussed in groups according to their major cause. Topics discussed include; design deficiency, drafting and detailing errors, concrete mix problems, supervision omission, frost protection defects, bearing wall deficiency, foundation deficiency, faulty erection techniques, temperature and shrinkage, secondary stresses, and formwork.

The discussion of temperature and shrinkage failures begins by noting that though few examples of actual collapse exist, considerable cracking and spalling can be attributed to these effects.

Examples of complete failures due to these effects include the collapse of a rigid frame warehouse at Wilkins Air Force Base, Shelby, Ohio, on August 17, 1955, and an identical warehouse at Robins Air Force Base, Macon, Georgia, on September 5, 1956. Among the conclusions of the final report on these collapses was that the expansion joints were frozen and did not operate as intended. This in turn built up large stresses due to a rapid temperature fluccuation. The rigid frames then failed by shear in the roof beams. These failures led to increased research into shear reinforcement in beams, but it is worth noting that the primary cause of failure was the poorly designed expansion joints.

1958

18. Cohn, Earl B., and Wall, W.A., "Military Personnel Records Center Built Without Expansion Joints," ACI Journal, Proceedings, V. 54, No. 12, June, 1958, pp. 1103-1110.

This is a report of the design and construction of the Military Personnel Records Center, in St. Louis, Mo. At the time of this report, it was one of the 20 largest buildings in the world. The most significant feature of the design was the omission of any expansion joints in the main building.

The reasoning used by the structural engineer in his decision not to use expansion joints was based on the fact that shrinkage and expansion due to temperature effects tend to offset each other. If the shrinkage can be accommodated in the sequence of construction, then the expansion should never exceed the shrinkage and any additional stresses can be controlled by extra reinforcement.

Considerable cracking occurred in the structure during construction. After investigation, it was determined that these cracks were caused by the extremely hot weather during concrete placement and the restraint to shrinkage offered by the foundation. Load testing indicated no major loss in strength.

Noting the causes of the cracking experienced, the report concludes that this structure demonstrates the feasibility of constructing large buildings without permanent expansion joints.

See reference 39 for a report on the fire performance of this structure.

19. Critchell, Peter L., Joints and Cracks in Concrete, Contractors Record Limited, London, 1958, 232 pp.

This book thoroughly covers the subject of cracks in concrete structures and the joints used to control them. The author explains that while concrete has many advantages over other structural materials, it has several properties, primarily shrinkage and movement due to moisture and temperature changes, which require close attention and careful detailing to minimize their detrimental effects.

Subjects discussed in this book include the movements to be accommodated, location and sizing of joints, joint design, common defects in concrete related to improper joint design, inspection and maintenance of joints, and conditions which require special assessment.

Each of the topics is fully discussed by the author. He gives his recommendations for the spacing and location of contraction and expansion joints. There are numerous details and photos of joints in service and descriptions of how the joints were constructed. Most interesting are photos showing structural distress due to poor joint design.

1960

20. Billig, Kurt, "Expansion Joints," Structural Concrete, London, McMillan and Co., Ltd., 1960, pp. 962-965.

This chapter is a summary survey of the purpose, location, and construction of expansion joints in concrete structures. Due to the cost and maintenance problems involved with expansion joints, the reader is advised to avoid the use of expansion joints wherever possible.

In general, structures with a length or width greater than 100 feet should be subdivided by joints. Joints should be located at abrupt changes in height, shape in plan, or foundation.

During the discussion of the required width of expansion joints, the statement is made that joints should be sufficiently wide to allow for large movements in case of fire.

Other topics include protection against dynamic effects, relation to reinforcement, types of expansion joints, watertightness, and continuity. Several example details are provided.

21. Wijler, A., "Strains in Reinforced Concrete Caused by Daily Temperature Changes in Desert Regions," Proceedings of the RILEM International Symposium on Concrete and Reinforced Concrete in Hot Countries, Israel Institute of Technology, Haifa, July, 1960, 18 pp.

The author is principally concerned with investigating the deteriorating effects of the daily temperature variations in desert climates. The author studies the stresses caused by the hot days and cool nights in a reinforced concrete building located in Israel.

In discussing the factors which determine the amount of deterioration, he states that the proper width and spacing of expansion joints is of vital importance. The author states that in hot countries, the common distance for the spacing of expansion joints is 10 meters.

1964

22. Feld, Jacob, Lessons from Failures of Concrete Structures, ACI Monograph No. 1, American Concrete Institute, Detroit, 1964, 179 pp.

This is a survey of significant failures in concrete structures. Subjects are discussed in groups based on the major cause of the structural failure. The groups are design deficiency, drafting and detailing errors, concrete mix errors, supervision omission, temperature and shrinkage effects, and others.

In discussing temperature and shrinkage problems, it is noted that few failures can be directly attributed to these effects; but even though safety is the prime consideration of the structural engineer, good engineering also calls for provisions which preclude structural damage and distress at a minimum cost. This requirement calls for consideration of temperature and shrinkage effects.

The nature of the problem is discussed and typical solutions are presented. It is noted that the suggestion in older literature to provide 0.3 percent reinforcement of the cross section has been shown to not always prevent the formation of cracks.

Several examples are discussed in detail to illustrate the possible problems that could occur, if these effects are ignored.

1966

23. Osgood, Everett W. and Keith, James M., "Construction of Accelerator Housing at the Sanford Linear Accelerator Center," ACI Journal, Proceedings, V. 63, No. 4, April 1966, pp. 425-439.

This report, written during the construction of the 10,000 foot linear electron accelerator at Stanford University, describes special precautions used to satisfy the severe dimensional tolerances required.

The accelerator is housed in a 10 by 11 foot concrete tunnel, placed about 25 feet below the ground surface. The roof and floor were 2 feet thick, and the walls 1-1/2 feet thick. Only nominal reinforcement was placed in the longitudinal direction, and no expansion joints were used. Shrinkage was controlled through the concrete mix proportions, the temperature of the fresh concrete, continued cooling of the placed concrete, and continuing water curing.

Construction joints were epoxy injected. The nature of all observed cracking is described. Construction joints opened to some degree. At the time the article was written, the structure had not been put into operation, at which time it would undergo a gradual rise in temperature of about 40 degrees fahrenheit. The authors conclude that this project demonstrates that the procedures they have used to control the drying shrinkage were successful.

1969

24. Boswell, P., "Detailing for Movement in Precast Concrete Structures," Design for Movement in Buildings, The Concrete Society, London, 1969, 13 pp.

While most papers presented in this publication by the Concrete Society are concerned with load induced movements, this paper describes joints used for expansion, contraction, rotation and differential movement.

Numerous details of expansion joints for several types of concrete construction are presented, with particular attention given to precast construction. Figures show the classical modes of failure that result from neglecting thermal movements.

It is stressed that joints should be located based on a detailed consideration of the structure in question and not by rules-of-thumb. Design for movement does not necessarily mean the provision of movement joints; it is sometimes preferable to design the structure as a whole to accept these movements.

25. de Courcy, J.W., "Movement in Concrete Structures, Regional Recommendations and Standards for Design and Construction," Concrete (London), V. 3, No. 6, June 1969, pp. 241-246, V. 3, No. 7, July 1969, pp. 293-297, and V. 3, No. 8, August 1969, pp. 335-338.

The author has assembled information relating to movement in concrete structures. This information was drawn from 48 specifications, codes of practice, and building regulations. Although recognizing that these publications are by the nature not exhaustive, often uneven in coverage, and often restricted to a limited range of structures or locale, they provide a wide range of recommendations.

These recommendations for assessing and controlling movement in concrete structures are arranged under 16 headings. Recommendations are presented under each heading, along with a comparison and analysis.

The result is a very concise description of how these numerous publications handle design temperatures, expansion and contraction joint location, shrinkage, creep and other topics related to movements in concrete structures.

1970

26. Mann, O. Clarke, "Expansion-Contraction Joint Locations in Concrete Structures," Designing for the Effects of Creep, Shrinkage, and Temperature in Concrete Structures, SP-27, American Concrete Institute, Detroit, Michigan, 1970, pp. 301-322.

This paper is primarily concerned with movements in concrete structures caused by drying shrinkage and temperature change. The theme of the work is that if shrinkage and temperature change could be determined in a rational manner, and then if they could be controlled, the number of contraction joints could be reduced.

Using the concepts of total heat content and heat transfer, an expression is developed to give the temperature of fresh concrete from the moment of placement as it varies with time. This results in a temperature-shrinkage history for a particular structure. From this history, the maximum temperature induced volume change expansion and shrinkage for the structure can be determined.

By comparing the maximum volume reduction in a normally constructed reinforced concrete structure and in a structure where the shrinkage and temperature drop have been reduced, the author determines that the contraction joint spacing in the controlled structure can be reduced proportionately from the spacing used in the normal structure.

27. Manufacturer's Notes, "Joints and Sealants," Civil Engineering and Public Works Review, V. 65, No. 769, August 1970, pp. 902-908.

As a reader service, a compilation of manufacturer notes dealing with products available for expansion or other movement joints is presented. In these notes, manufacturers describe their products and their range of application. Over 20 joint product manufacturers are included in the compilation.

28. Martin, Ignacio and Acosta, Jose, "Effect of Thermal Variations and Shrinkage on One Story Reinforced Concrete Buildings," Designing for the Effects of Creep, Shrinkage, and Temperature in Concrete Structures, SP-27, American Concrete Institute, Detroit, 1970, pp. 229-240.

ACI 318 states that consideration shall be given to the effects of forces caused by shrinkage and temperature changes. One way to comply with this requirement is to provide expansion joints, limiting the size of each structural segment to a length for which these effects can be neglected.

A method for the spacing of expansion joints is presented. The study is limited to one story reinforced concrete buildings. An empirical equation was formulated to determine the maximum allowable expansion joint spacings based on the analysis of 98 structural models using ACI 318 as the design criteria. A deflection criteria equation is also developed.

The formula proposed is said to be conservative for all the cases studied, but further exploration for other cases is recommended.

29. Rogers, Paul, "Temperature Changes on Reinforced Concrete Frame of Bakery Structure," Designing for the Effects of Creep, Shrinkage, and Temperature in Concrete Structures, SP-27, American Concrete Institute, Detroit, 1970, pp. 241-245.

The design of a two and four story, reinforced concrete bakery building for temperature effects is described. A section of the structure with the overall dimensions of 540 by 310 feet was required to be constructed without any expansion joints. A wide temperature range had to be accommodated due to the start up and shut down of the bakery ovens. Also, no cracks were permitted due to the risk of contamination from microscopic plant and animal life.

The author discusses how the temperature loading was determined and how it was integrated with the other loading conditions. The temperature loading on the structure increased negative girder moments by 10 percent, column end moments by 200 percent, and axial forces in the exterior columns by 6 percent.

The author concludes that through proper analysis, adequate design, and good construction, cracking due to temperature change can be avoided.

30. Shirley, D.E., "Flexible Seals for Movement Joints in Concrete Structures," Civil Engineering and Public Works Review, V. 65, No. 769, August 1970, pp. 875-880.

This article summarizes current knowledge and practice in relation to the sealant material used for expansion joints. It notes that, while it is not too difficult to design a movement joint to exclude rain, sometimes the joint must also provide a seal against extremes of temperature, noise, pressure, or other elements.

After the requirements for the ideal sealant are discussed, the author proceeds to classify commonly used sealant materials and describe the structure type to which they are best suited.

The reader is cautioned that the choice of joint spacing and the flexible joint sealant must be considered in the early stages of the design process.

1971

31. ACI Committee 350, "Concrete Sanitary Engineering Structures (ACI 350-71)," ACI Journal, Proceedings, V. 68, No. 8, August 1971, pp. 560-577.

This report is for use in the design of conventional reinforced concrete sanitary engineering structures. Principal types of structures included in this category are tanks, reservoirs, manholes, wetwells, pump stations, settling tanks, and similar installations.

The report provides information concerning the design, materials and mix, construction, and protection against chemical deterioration. In sanitary engineering structures, durability, permeability, and crack control demand special attention.

Recommended allowable concrete and steel stresses are provided that are somewhat more conservative than for normal concrete design. These stresses are governed mostly by the tensile strength of concrete. The primary reason that lower stress values are recommended for sanitary engineering structures is to prevent tensile cracking of the concrete.

Expansion joints are suggested for noncircular structure having a dimension of 120 feet or more in any direction. The desirable expansion joint spacing is not more than 50 to 60 feet for members exposed to the atmosphere, or 80 to 100 feet for members completely underground. Recommended expansion joint widths are provided for specified joint spacings.

Construction joints should be located so they do not impair the strength of the structure. Typical vertical spacings are 10 to 15 feet, and typical horizontal spacings are 20 to 30 feet.

Information on design requirements for vibrating equipment and impact are also provided.

32. Aroni, Samuel, "Observations of Temperature Effects on Flat Slab Reinforced Concrete Building," Proceedings of the 2nd RILEM International Symposium - Concrete and Reinforced Concrete in Hot Countries, Technion, Israel Institute of Technology, Haifa, August 2-5, 1971, pp. 39-50.

This report is the result of some unforeseen temperature related effects that occurred during the testing of a flat slab. The observations described are not the result of testing designed to investigate the effect of temperature changes.

The subject of the investigation was a two story reinforced concrete flat slab building, 600 feet long and 46 feet wide. The report describes how the first floor slab was divided into six sections of 100 feet, separated by expansion joints. Brick partition walls were used to separate the space into various rooms.

Extensive cracking was observed on the underside of a portion of the first floor slab. This prompted a load test to check the structural integrity of the slab.

Due to practical reasons, it was not possible to apply an uniform load, as required by the governing building code. Instead, a concentrated load was applied to the center of the slab. The load was applied with a screw jack reacting against the roof slab. A load cell was placed above the screw jack to measure the applied load.

During the course of the long-term load test, lasting a total of 88 hours, the outside temperature dropped. During periodic readings of the load cell, an increase in load of 70 percent was noted. It was speculated that the temperature drop caused the roof to bend downward, throwing load onto the jacking apparatus testing the first floor slab. To confirm this speculation temperature readings over the period of the testing were obtained. A very high degree of correlation was evident between the outside temperature and the load cell reading.

The results of this test were presented to emphasize the importance of thermal stresses in the presence of rigid partition walls, as well as the need for further research.

33. Hendry, A.W., and Nourini, G.A., "The Spacing of Expansion Joints in Concrete and Masonry Structures," Proceedings of the 2nd RILEM International Symposium - Concrete and Reinforced Concrete in Hot Countries, Technion, Israel Institute of Technology, Haifa, August 2-5, 1971, pp. 51-68.

This paper derives a method to determine the required spacing of expansion joints based on maximum allowable tensile stresses in roofs and walls of reinforced concrete. After briefly reviewing the nature of the problem and the contributing factors which affect the cracking of concrete roofs and walls, formulae for thermal stresses are derived using a strength of materials approach. From these formulae, the distance to build up the maximum permissible tensile stress for the material is determined. This distance is termed the "critical fissure length." The distance between expansion joint locations is twice this distance.

Design graphs are presented along with the discussion, and several example solutions are provided.

1972

34. Fintel, Mark, "Theme Report," Structural Design of Tall Buildings-Creep, Shrinkage, and Temperature Effects, ASCE-IASBE International Conference and Proceedings, Vol. III-25, 1972, pp. 741-753.

Two decades ago, the consideration of shrinkage and temperature effects on the behavior of buildings was a purely academic subject. But now, due to the recent advances in higher strength materials and the better understanding of basic structural behavior, we are building more flexible structures with lower factors of safety.

The margin of the allowable stress which can be utilized by the secondary stresses of creep, shrinkage, and temperature variations has been reduced. Thus, the consideration of these stresses have now become a primary problem in some structures, particularly in very tall or long structures.

This, the theme report of the conference, summarizes the nature of the problem, and while doing so, touches on some of the analysis procedures and solution methods in current usage.

Though primarily concerned with how to deal with secondary stresses in tall buildings, the case of a long horizontal structure is also discussed. Four categories of joints are described, expansion joints, construction joints, contraction joints, and shrinkage strips. It is stated that the trend in recent years is to use expansion joints less frequently, because it is recognized that the concrete will normally never occupy a larger volume than at the moment of casting. There is still considerable need for developmental work to determine rational approaches to expansion joint spacing, but it is noted that the simplicity of the subject does not attract the interest of the academic community.

35. Holland, Eugene P., "Horizontal Effects - Length Changes Due to Shrinkage and Temperature; Expansion, Construction, and Control Joints in Structural Slabs," Structural Design of Tall Buildings - Creep, Shrinkage and Temperature Effects, ASCE-IASBE International Conference Proceedings, V. III-25, 1972, pp. 305-309.

There is a general disregard for the horizontal component of shrinkage and temperature volume changes in buildings, as evidenced by the absence of research on the subject. Due to this, the designer is forced to rely on judgment and/or past experience. The point is made that no two structures are alike, and it is often incorrect to extrapolate from one to another.

Methods used which deal with excessive cracking due to temperature and shrinkage are described. If precautions are taken with the mix proportions in conjunction with proper material constituents and temperature controls of the fresh concrete, shrinkage can be reduced up to 40 percent.

Expansion joints are not generally used except for roofs and exposed elements, such as continuous balconies, spandrel beams, and walls where the effects of temperature changes are most pronounced. Instead, shrinkage strips are preferred.

A shrinkage strip is a temporary gap left in a wall or floor that allows a portion of the drying shrinkage to take place prior to making the structure fully continuous. The major problem with the use of shrinkage strips is that they are not compatible with today's fast track construction. Extra time is required to go back to cast the gaps left at the shrinkage strips. Construction is also impeded due to the shoring which is left up longer.

The provisions of ACI 318 for minimum reinforcement are discussed, and the statement is made that there appears to be no rational basis for this criteria.

The author requests more research on the subject.

36. Rankine, John, "Summary Report," Structural Design of Tall Buildings - Creep, Shrinkage and Temperature Effects, ASCE-IASBE International Conference Proceedings, V. III-25, 1972, pp. 831-838.

This report is a summary of the papers presented at this conference.

The author discusses building as an art. The great builders of the past were able to achieve magnificent and spectacular structures, not because of their ability to compute, but because of an intimate knowledge of the materials at their disposal and an understanding of the basic forces of nature. Today's designer is faced with an increasing number of new materials, and with additives to old materials which change their behavior; all this makes it a greater challenge to build well.

The name of the game today is money, and this is causing us to build to tighter specifications. This exacerbates the effects of creep, shrinkage, and temperature variations. Every tall building or long structure needs to be thoroughly investigated for these effects on its particular configuration and materials to ensure they are not troublesome.

1974

37. Expansion Joints in Buildings, Technical Report No. 65, National Academy of Sciences, Washington, D.C., 1974, 43 pp.

This report was prompted by the significant differences found in the various guidelines used for locating and sizing expansion joints in federal buildings. The differences were so great as to suggest that some of the guidelines were in error, causing either omission of joints where needed, or inclusion where not. Both instances add extra cost to the structure and, in the first case an increased risk of structural distress or failure. The National Academy of Sciences undertook the study in order to develop more definitive criteria for the use and spacing of expansion joints.

Three major sources were used in this study. First, a review of the current practices of federal agencies was conducted. Second, an examination was undertaken of an unpublished report in which horizontal dimensional changes in nine federal buildings were related to recorded temperature changes. And third, in the course of the study, the committee formulated and conducted an analysis of a typical multi-story two-dimensional building frame.

Based on their investigation of these sources, the committee developed an empirical method to determine the need for expansion joints. By use of one figure relating allowable building length to design temperature change, and then applying appropriate factors, their method determines the spacing required for the placement of expansion joints. This method takes into account the type of construction, the location of the building, any provision for temperature control, the type of framing, connection to the foundation, and the construction materials.

Also presented is an approach to be used in a detailed analytical or computer solution, if the empirical solution appears too conservative.

To back up the recommendations, the report includes a detailed discussion of the analysis and findings. The appendices include the computer printout of the elastic frame analysis and the necessary seasonal temperature data for the United States.

38. Fintel, Mark, "Joints in Buildings," Handbook of Concrete Engineering, New York, New York, Van Nostrand Reinhold Company, 1974, pp. 94-110.

Discusses the subject of joints in concrete buildings, each type of joint is described, and its purpose explained. Construction joints, contraction joints, expansion joints, shrinkage strips, isolation joints, and hinges are discussed.

The report comments on the widely varying opinions as to the need for expansion joints and requirements for their spacing. Detailed recommendations from several sources are given.

This chapter includes many joint details.

1975

39. Culver, Charles G., and Crist, Robert A., "Fire Performance of Military Record Center," ACI Journal, Proceedings, V. 72, No. 4, April 1975, pp. 164-166.

The performance of the Military Record Center, located in St. Louis, Missouri is described due to a severe fire that occurred there on July 12, 1973.

The building, built in 1956, is a six story reinforced concrete flat slab warehouse structure of extremely large floor area. The plan area per floor is about four and three quarters acres. The most notable feature of the building is that it was built without any expansion joints.

The fire occurred on the sixth floor and caused about thirty percent of the roof slab and supporting columns to collapse. Extensive damage to the columns that did not collapse is described due to the large horizontal expansions of the roof slab. After the fire, residual horizontal expansions were measured up to twenty-three inches.

The sixth floor slab and all lower floors received minimal damage. This was attributed to the insulating effect provided by unburned paper that accumulated on the sixth floor and the fact that once the roof slab columns sheared off very little load was transferred into the lower floors.

The author makes no comment on what effect the absence of expansion joints had on the performance of this building to fire. See reference 18 for a report on the initial construction of this building.

1976

40. Yee, Alfred A., "Prestressed Concrete for Buildings," Journal of the Prestressed Concrete Institute, V. 21, No. 5, September-October 1976, pp. 112-157.

This article is a historical summation of two decades of prestressed concrete and a survey of current practice. The author discusses economic factors, special design considerations, the physical capabilities of the material, and the advantages inherent in prestressed concrete construction.

General design practice for prestressed concrete buildings is to avoid the use of expansion joints. Monolithically reinforced decks of up to 700 feet in length are reported that have performed well. Expansion joints are avoided to limit damage due to earthquakes and the substantial extra cost for additional shear walls, moment resisting frames, and expansion joint hardware. Repair and maintenance costs for expansion joints are also high over the life of a building.

1977

41. ACI Committee 350, "Revisions to Concrete Sanitary Engineering Structures (ACI 350R-71)," ACI Journal, Proceedings, V. 74, No. 6, June 1977, pp. 235-237.

This revision to ACI 350-71 contains several important additions to the original report.

The recommended allowable concrete and steel stresses are tied to the use of Z values. The recommended stresses are given for the sanitary exposure condition and for the maximum Z value as defined in ACI 318-71. The Z values where derived to control flexural cracking.

Procedures are presented for the seismic design of sanitary engineering structures. In fluid storage tanks, the hydrodynamic mass of the fluid must be considered in the load determination. In addition the structure must be designed for the seismic effects of both external earth pressure and the structure dead weight.

The report's recommendations concerning expansion and construction joints are the same as in the previous report. No specific recommendations are given for contraction joints.

42. PCI Design Handbook Precast Prestressed Concrete, Second Edition, Prestressed Concrete Institute, Chicago, 1978, 370 pp.

The primary objective of the PCI Design Handbook is to make the design and construction of prestressed and precast concrete buildings easier by providing information to assist the designer in achieving an optimal design.

The handbook covers topics including assembly, concepts, product information and capability, design, analysis, connection design, and related topics in precast and prestressed concrete building design.

Section 4.3 of the handbook concerns the topic of expansion joints. Expansion joints are most often located by 'rules of thumb.' It is noted that it is desirable to have as few expansion joints as possible. The method presented in this handbook for the spacing and location of expansion joints is the same method as developed in the National Academy of Science's publication, Expansion Joints in Buildings. See reference No. 37 for a description of this publication.

1978

43. Varyani, U.H., and Radhaji, A., "Analysis of Long Concrete Buildings for Temperature and Shrinkage Effects," Journal of the Institution of Engineers (India), V. 59, Part CI 1, July 1978, pp. 20-30.

This paper develops a method for the inclusion of the horizontal effects of temperature and shrinkage in the structural design of concrete buildings. This method determines column moments from the expansion or shrinkage of a floor and then uses moment distribution to find the moments in columns and beams due to these effects.

The paper develops an expression for the expansion joint spacing required to avoid extra reinforcement beyond that for gravity loads. Using this expression, the current building code requirements (India) are reviewed. The recommended expansion joint spacing of 45M found in IS 456-1964, 'Code of Practice for Plain and Reinforced Concrete,' agrees with the analyses only for rectangular buildings with medium story heights and flexible columns in moderate climates. A table presents the recommended values for expansion joint spacing taking into account the major parameters that affect joint spacing.

1979

44. Janssen, W., "Water-Proofing of Concrete Immersed Tunnels," Consulting Engineer, V. 43, No. 2, February 1979, pp. 45-46.

This report is concerned with methods used to waterproof concrete tunnels located below the water table. The problems caused by concrete shrinkage, expansion and contraction and the historical solutions for providing watertight joints are reviewed.

Until recently an expensive waterproofing layer was provided around every tunnel. This consisted of several layers of fiberglass or other non-organic material, impregnated with asphalt. Recent advances in tunnel construction technology have eliminated the need for this layer.

A major problem in tunnel construction is that when pouring the tunnel walls the shrinkage of the wall causes differential movement between the wall and the floor. To counteract this problem, the author describes methods which combine a reduction in the initial temperature of the concrete in the walls with a system of chilled water pipes embedded in the walls. At the same time, the floor is heated to reduce the temperature differential between the floor and walls.

Improved, specially designed expansion joints are described which allow for the elimination of the waterproofing layer.

1980

45. ACI Committee 224, "Control of Cracking in Concrete Structures (ACI 224R-80)," Concrete International: Design and Construction, V. 2, No. 10, October 1980, pp. 35-76.

This report presents a detailed description of the significant causes of cracking in concrete structures and recommended procedures to prevent cracking.

Cracking is described on a microscopic and a macroscopic level. The results of recent research into the nature of cracking is presented and significant conclusions outlined. A description of and methods for control of cracking due to shrinkage, flexural stresses, for mass concrete, and for layed systems are given.

The amount of shrinkage due to drying is said to be only one of many factors affecting cracking. The importance of the degree of restraint in the structure, the modulus of elasticity, and creep of the concrete is also described. The effects of aggregate size, water cement ratio, the temperature of the fresh concrete, admixtures, and curing procedures are described in relation to preventing shrinkage and cracking.

The use of contraction joints is said to be the most effective method to prevent the formation of unsightly cracks. For walls and parapets, contraction joints are recommended to be placed at a distance of one to three times the wall height. The importance of detailing the contraction joint locations on the plans is also emphasized.

1981

46. Cook, G.R., and Goel, A.P., "Joints in Water Retaining Structures," Joint Sealing and Bearing Systems for Concrete-Structures, SP-70, American Concrete Institute, Detroit, 1981, pp. 439-453.

The various types of joints in concrete structures are discussed, giving special consideration to those in water retaining structures. Construction joints, expansion joints, contraction joints, and structural sliding or hinged joints are discussed in turn.

The spacing of contraction and expansion joints are given with reference to ACI 350R-77, "Concrete Sanitary Engineering Structures" (Reference 41). Joint materials, joint design, and standard details are also presented.

The conclusion of the paper is that, while joints in water retaining structures are still a much debated subject, proper planning, design, and construction can produce trouble free joints.

47. Klein, Fran; Hoffman, Edward S.; and Rice, Paul F., "Application of Strength Design Methods to Sanitary Structures," Concrete International: Design and Construction, V. 3, No. 4, April 1981, pp. 35-40.

This article describes the direction that the Task Committee on the Structural Design of ACI Committee 350 is taking in their revision of ACI 350R-77, "Concrete Sanitary Engineering Structures" (Reference 41).

The reasons requiring a revision are outlined. These include problems with the continued use of working stress design, since recent graduates have little training in this method, and the criticism that potential savings in reinforcing steel were being neglected.

The major revision to the report is the adoption of ultimate strength design for sanitary structures. To limit cracking under service loads, the use of "sanitary exposure coefficients" are included in the proposed design procedure. These coefficients increase the load factors as used in ACI 318.

A graph is presented which gives the minimum shrinkage and temperature reinforcement for given contraction joint spacings.

48. Scarino, John H., "Evolution of Watertight Construction Joint Design for Sanitary Engineering Structures," Concrete International: Design and Construction, V. 3, No. 4, April 1981, pp. 48-52.

This article describes the evolution of watertight construction joint design. Starting with the turn of the century, an historical summary of joints and of joint design criteria is presented. Recent developments in joint design are described, along with a discussion of unresolved questions concerning joint design and behavior.

Design criteria for keyed joints are at best questionable. It is stated that waterstops have a weakening effect on the joint. The failure modes of various keyed joints were analyzed by the author.

As a qualitative confirmation of his theoretical analysis, clay micro-specimens of joints were tested.

The author concludes that there are still many questions concerning the behavior of watertight construction joints. Actual testing of full scale sanitary engineering structures is suggested as the only means for advancing the state of knowledge.

49. Williams, Joe V., Jr., "Recommendations for the Use of Shrinkage-Compensating Concrete in Sanitary Structures," Concrete International: Design and Construction, V. 3, No. 4, April 1981, pp. 57-61.

The history of shrinkage-compensating concrete is presented along with a discussion of the advantages to be gained from its use. The primary reason for using shrinkage-compensating concrete is to reduce and potentially eliminate cracking due to drying shrinkage. As a result, larger placement areas are permitted, reducing the number of construction joints and waterstops. No contraction joints are said to be necessary for shrinkage-compensating concrete.

A quantitative relationship between construction joint spacing and the shrinkage steel ratio is presented, along with descriptions of various casting sequences used for structures built with either portland cement concrete or shrinkage-compensating concrete. Specific details are presented to accommodate the expansion of cast-in-place walls built with shrinkage-compensating.

Recommendations for the mix design, admixtures, and curing procedures to be used with shrinkage-compensating concrete are also outlined.

50. Wood, Roger H., "Joints in Sanitary Engineering Structures," Concrete International: Design and Construction, V. 3, No. 4, April 1981, pp. 53-56.

Joints are a major factor in the design and construction of sanitary engineering structures. Early consideration must be given to the joint system, because of the effect of joints on the structural system. Joints, or the lack of joints have caused more problems than any other single item in concrete construction.

The approach presented in this article is based on the author's own experience as to what works best for his localities and materials. The purposes, locations, types and details of joints are discussed. Expansion, contraction, partial contraction, and construction joints are described in detail. The relation between joint spacing and reinforcement ratios is given.

The importance of the joint detailing is emphasized, particularly waterstops. Many times the position of the waterstop is not given sufficient attention, resulting in designs that are crowded and difficult to construct.

Joint details are typically one of the most troublesome aspects in concrete structures.

1982

51. Building Movements and Joints, Portland Cement Association, Skokie, Illinois, 1982, 64 pp.

This text covers the entire topic of building movements--what causes them and how they can be controlled to eliminate structural distress.

The processes which produce these motions are discussed for both the unrestrained and the restrained case. The restrained case represents the actual conditions found in buildings. Movements due to special loading conditions, settlements, and construction procedures are discussed in addition to shrinkage, temperature effects, chemical changes, and creep.

In describing the methods to be used to protect against these motions, the text describes the use of contraction joints, expansion joints, construction joints, and joints in slabs on grade.

Recommended spacings for contraction joints and expansion joints are provided. The method to determine the spacing of expansion joints follows the procedure developed in the Technical Report No. 65 by the National Academy of Sciences, Expansion Joints in Buildings. See reference No. 37 for a description of this publication.

Although the causes and exact prediction of cracks in concrete structures is complex, it is shown that the remedies are usually quite simple.

52. Price, Walter H., "Control of Cracking of Concrete During Construction," Concrete International: Design and Construction, V. 4, No. 1, January 1982, pp. 40-43.

This article provides a description of the principal types of cracking that can occur in both plastic and hardened concrete, as well as recommendations to avoid their occurrence.

Cracks in plastic concrete are caused by differential settlement within the concrete mass, plastic shrinkage of the concrete surface caused by rapid loss of water, or even a combination of surface hardening and interior settling. The author provides recommendations to guard against these problems.

Excessive finishing is also a poor practice, since cracking in plastic concrete can be caused by improper floating or troweling.

The problem of shrinkage is described for hardened concrete. With a coefficient of shrinkage of 0.05 percent, concrete will shrink about 1/16 inch in 10 feet. This develops a tensile stress of 1500 psi, or about 3 times the ultimate tensile strength of the concrete. So the concrete must crack. The author recommends the placement of contraction joints at about 15 to 20 foot intervals in unreinforced concrete.

The coefficient of expansion is about 0.0000055 inch per degree F. This is equal to a 0.025 inch contraction per 10 feet for a 40 degree F drop in temperature. To control cracking due to shrinkage and temperature changes, the author says that reinforcement or prestressing, which keeps the concrete in compression and uncracked, can be used.

Other causes of cracking include the alkali-aggregate reaction, excessive carbon dioxide resulting from using fuel heaters in enclosed areas during frost protection operations, corroded reinforcement, embedded aluminum conduits, and formwork that restrains concrete shrinkage.

1983

53. ACI Committee 350, "Concrete Sanitary Engineering Structures (ACI 350R-83)," ACI Journal, Proceedings, V. 80, No. 6, November-December 1983, pp. 467-486.

This report is a further revision of ACI 350-71 and ACI 350R-77.

A major addition in this revision is the provision of "sanitary durability coefficients," which allow the use of ultimate strength design for sanitary engineering structures. The coefficients are applied to the total factored design load "U." Basically they perform the same function as the lower allowable stresses used in working stress design, which is to keep the working stresses at a low level and thereby prevent the formation of cracks.

The topics of shrinkage, expansion and the appropriate jointing are given a more thorough coverage in this new revision. The amount of shrinkage and temperature steel is given as a function of the distance between contraction or partial-contraction joints.

Expansion joints are suggested to be placed at abrupt changes of configuration, and preferably at intervals not to exceed 120 feet. The designer is cautioned to consider the effect of thermal and moisture conditions during construction and periods when the tank might be empty.

Contraction joints should not be placed over 30 feet apart unless additional temperature and shrinkage reinforcement is provided. Both full and partial contraction joints are detailed. The spacing of a partial contraction joint should be two-thirds that of a full contraction joint.

1984

54. ACI Committee 224, "Causes Evaluation, and Repair of Cracks in Concrete Structures (ACI 224.1R-84)," ACI Journal, Proceedings, V. 81, No. 3, May-June 1984, pp. 211-229.

This report presents information to guide the practitioner in the evaluation and repair of cracks in concrete structures. The causes of cracking and the procedures normally used to control that cracking are described. Cracking of both plastic and hardened concrete are discussed.

Cracking due to drying shrinkage or thermal stresses can be controlled by properly spaced contraction joints and steel detailing. Properly designed walls are said to have contraction joints spaced from one to three times the wall height.

Special care is indicated in the design and detailing of structures where cracking may cause major serviceability problems. It is noted that the minimum requirements of ACI 318, or even ACI 350 are not always adequate. Each specific structure must be considered for its own loads, environment, and special properties.

Techniques are described for the determination of the location and the extent of cracking for the selection of repair procedures. A survey of crack repair methods and their proper application is also presented.

55. "Office Pours Stairstepped," Engineering News Record, V. 212, No. 11, March 15, 1984, pp. 15-16.

This article describes a diagonal pouring sequence which allowed the contractor to eliminate expansion joints and avoid concrete shrinkage and drying problems in an office building.

The technique is a first for office building construction and was adapted from parking structure technology. The simple concept delays pouring of adjacent sections as long as possible to allow as much shrinkage to take place before continuity is established.

The pouring sequence, utilizing custom made movable formwork, staggers the pours vertically and horizontally in a pyramid shaped pattern.

56. Gogate, Anand B., "An Analysis of ACI Committee 350's Recommended Design Standards," Concrete International: Design and Construction, V. 6, No. 10, October 1984, pp. 17-20.

The author provides a critique of ACI 350R-83, "Concrete for Sanitary Engineering Structures." The author defines a good design in reinforced concrete as meeting certain ultimate objectives. These objectives are outlined as follows: the structure should develop no more than hairline cracking, the crack width should be small, the probability of failure should be within acceptable limits, the structure should be buildable, and the structure must not be prohibitively expensive.

The author concludes that the report goes a long way towards meeting these objectives. There are several areas, however, where he finds the report lacking. The procedures for arriving at the effective amount of reinforcement and the spacing of joints to control cracking due to shrinkage and temperature are still largely empirical. This is because the effects of shrinkage, creep and temperature changes cannot accurately be quantified. This area will continue to be a major area of investigation.

The Gergely-Lutz equation has been used satisfactorily to control flexural cracking for members with primarily one-way action. However, the author questions the use of these equations for members with two-way action, or for members in tension. He suggests that in future development of this report, more appropriate equations should be used.

The buildability of a structure is greatly influenced by details of such things as horizontal wall joints. The author notes that the current report continues to endorse the use of keyways in these joints, despite research which has shown that the use of a keyway may be unnecessary and weaken the structure. It is noted that the use of keyways might be eliminated in the near future.

57. Rice, Paul F., "Structural Design of Concrete Sanitary Structures," Concrete International: Design and Construction, V. 6, No. 10, October 1984, pp. 14-16.

This article outlines the major objectives and the methods used to achieve them in ACI 350R-83, "Concrete Sanitary Engineering Structures." Two main reasons are given as to why this revision was necessary. The committee wished to take advantage of grade 60 reinforcing bars, which are now standard and to incorporate the strength design method into sanitary structure design.

To eliminate a two step design method, while using strength design procedures, the committee has developed "sanitary durability coefficients" that are used to regulate the stress under service loads to correspond closely to Z=115. The "sanitary durability coefficients" are applied to the design load, U, as computed using ACI 318.

The author noted that compared to ordinary structures, sanitary engineering structures have a proportionally larger amount of reinforcement devoted to controlling cracks caused by shrinkage and temperature change. The committee found that the percent of reinforcing steel required to prevent cracking was directly related to joint spacing. They also found that the required percent dictated by ACI 318 would be sufficient only for very small joint spacings. The new report provides a chart which gives progressively larger recommended minimum percentages as the joint spacing increases.