

EXPANSION JOINTS IN LOW-SLOPE ROOFS

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It is frequently claimed that splits in BUR membranes occur from the failure to provide, or to properly locate, expansion joints in roof decks. While this may be true for differential movement, it has not been substantiated for cumulative movement expected in large, unbroken rectangular roofs generally found on low-rise buildings.

A review of engineering journals and roofing manufacturers' catalogues has failed to uncover a single case in which the empirically stated joint spacing can be analytically substantiated.

Most authorities agree that the complexity of structures and the large number of variables preclude an analytical approach to the problem. However, it is precisely these variables that illustrate the fallacy of applying simple rules of thumb universally to different types of construction, with different degrees of risk, located in different climates.

This paper will review the current state of the art with respect to the location of expansion joints in roof decks. It will discuss differential and cumulative movement in decks and trace the historical development of empirical locations published for them. A more rational approach for locating joints will be suggested. The paper will also show that cumulative movement in roof decks is unrelated to splitting in built-up roofs.

The scope of this paper is limited to a discussion of low sloped roof decks with BUR membranes on framed, one- and two-story buildings. It does not cover roofs on load bearing masonry walls.

BACKGROUND

Design Strategies

Buildings are dynamic and respond to a variety of externally and internally generated forces that produce movement or stress. The most significant forces are those produced by temperature and moisture changes. Creep in concrete must also be considered, as well as seismic forces and those causing foundation movement; but these are not within the scope of this paper.

When the magnitude of stress concentrations exceeds the maximum strain capacity of the element, such as membrane, panel or frame, stress relief will occur in the form of a split, crack or deformation. Stresses may be set up within the element itself by environmental forces such as varying temperature or moisture, corrosion, wind or vibration, or stress may be transferred to the element. Methods to control this condition include:

- reducing the transfer of stress by isolation or buffering;
- increasing the strength of the element;
- reducing the level of loading, for example by changing color to reduce surface temperature or by ventilating to

control moisture;

- providing stress relief by means of a joint that will permit movement;

The selection of one or more of these methods cannot be made without establishing an acceptable level of risk.

Since it is often impractical to increase the size or tensile properties of members to resist all of these stresses without distortion, movement or isolation, joints are used to absorb them. If the expected movement is permanent and nonreversible, such as concrete shrinkage, control joints are used. If reversible movement is expected, expansion joints are used.

Since none of the nationally used building codes mandate expansion joints, the need for and location of these joints has been left to the designer's judgment.

The designer must identify and quantify the forces, evaluate their severity and understand the response of the various systems and materials to stress. The problem is complicated by the fact that most buildings are composed of a number of diverse materials and elements assembled with varying degrees of fixity under different environmental conditions. Thus, the designer cannot simply calculate movement using the coefficient of expansion and temperature differential because the building does not make the same simplifying assumptions nor arrive at the same result.

Development of Joint Spacing

Because joint locations are analytically indeterminate, a body of empirical rules has been developed over the years. There is general agreement for those locations where differential movement is predictable, but little consensus with regard to cumulative movement which occurs in large rectangular flat-roofed buildings.

One of the earlier references on the need for building expansion joints was made in 1940 by the American Society of Civil Engineers for concrete structures¹. They recommended a maximum of 200 feet on centers for severe conditions in localities with large temperature ranges and increased this spacing to 400 to 500 feet for "favorable conditions." But they noted that in roof construction the spacing may be as small as 100 feet. In 1947 Grinter² stated that a "common rule is... ½ inch to 100 feet with expansion joints spaced 200 to 300 feet on centers or possibly 400 feet."

In 1946, Time-Saver Standards³ suggested spacing joints 100 feet on centers for monolithic concrete, but noted that the "usual practice is 200 feet" citing Sternberg and figures published by the British Research Establishment. In 1955,

**The National Building Code of Canada discusses expansion joints in "Commentary D" but makes no specific recommendations.*

the fifth edition of Architectural Graphic Standards suggested 200 feet on centers for steel or concrete and 400 feet for brick or stone, but noted that "Because roofs move more than walls, expansion joints in roofs are sometimes placed closer than 200 feet."⁴

In 1965, Gumpertz⁵ recommended 150 feet. Griffin⁶ suggested 150 to 300 feet in 1970, but revised it in his 1982 edition to 200 feet. The latest published spacing is 100 feet (30m) stated by Rainger 1983.⁷

Roofing manufacturers began to include recommended expansion joint spacing in their catalogues in 1962. In that year, Owens-Corning Fiberglas called for 300 feet and Philip Carey 150 feet. Koppers recommended 200 feet in 1966 which was also by Philip Carey in 1969, Johns-Manville in 1971 and Celotex in 1974. In 1972 O.C.F. had revised its spacing to 200—300 feet.

At about the same time that the roofing manufacturers were jumping on the 200-foot bandwagon, the Federal Construction Council of the National Academy of Sciences⁸ was conducting a study "in the hope of developing more definitive criteria for expansion joints than have existed in the past" while noting that "Although relatively few serious problems attributable to inadequate provision for temperature-induced movement have been reported, significant differences are found in the various guidelines used for locating and sizing expansion joints, suggesting that at least some of the guidelines must be in error." This study proposed joint spacing somewhat greater than those recommended by both the roofing manufacturers and many authorities.

It is significant that the early expansion joint spacings were promulgated prior to World War II, when insulation was frequently omitted on concrete roof decks and was minimal on steel decks. Close joint spacing was necessary because the decks and supporting structures reacted quickly to ambient temperature changes. After the War, as more buildings were heated and then air conditioned, the need for greater thermal resistance increased and then became mandatory following the 1973-74 oil embargo. With increasing thermal resistance, the temperature of the deck and its supporting structure approached that of the controlled interior environment and there was less need to provide for thermally induced movement of the building frame from ambient temperature extremes. Today there appears to be little justification for continuing to limit the spacing of building expansion joints to 200 feet, particularly for roof decks.

There is even less justification for using a single limit for every building without considering the response of the structure, roof deck and cladding materials to the change in temperature to which they may be subjected, their freedom to move and the tolerable degree of risk. Since expansion joints, like any moving part are subject to fatigue failure, and as a consequence, to leaking, the decision to use them should be made with great care.

DIFFERENTIAL MOVEMENT

Where abutting structural systems, decks or materials differ, or where there is a substantial difference in their exposure or response to environmental changes and periodic forces, the probability of excessive stress concentrations is very high. This frequently occurs at a discontinuity and the joint can conveniently be designed to absorb the stresses and permit

differential movement. The more usual locations where stress concentrations can be expected are:

- where the materials of a framing system change, from steel to concrete for example;
- where beam or deck systems change direction;
- where deck materials or characteristics change, such as from steel to wood or from cast-in-place concrete to prestressed;
- where abutting structural systems differ in stiffness, such as where a single-story building joins a multi-story building or one with fixed column bases joins one with hinged column bases;
- where differential settlement may occur, such as at additions or where buildings on piles join those on spread footings;
- where the roof deck is supported independently of concrete or masonry walls with parapets;
- where exposure to ambient or interior temperatures vary, such as at canopies or between a freezer building and adjoining offices;
- where exposed concrete or wood framed construction is exposed to substantial and variable moisture differentials, such as between classrooms and a swimming pool.

Joints are also required where ends of simply supported long span beams or decks will rotate and open a joint greater than $\frac{1}{4}$ inch under live loads that create a deflection of $\frac{1}{240}$ of the span.

CUMULATIVE MOVEMENT

Although there is general consensus in the industry that joints are required at the above locations where differential movement is predictable, there is considerably less agreement on the need for expansion joints in large unbroken areas of rectangular roofs where cumulative movement may occur. As the Federal Construction Council states "the decision concerning the number and location of expansion joints . . . has been left primarily to the judgement of the designer on the basis of his intuition and experience,"⁸ because he does not have enough information available to make an analytical determination of the stresses involved. Consequently those lacking intuition or experience simply resort to published spacings.

In order to make an analytical analysis the designer requires precise information as to:

- the response of the structure and enclosing elements to thermal and moisture differentials;
- the change in temperature or humidity to which they may be subjected;
- their freedom to move;
- the amount of stress that can be absorbed without deformation;
- the tolerable degree of risk.

Response to Varying Temperatures and Humidities

There are many publications that list average coefficients of expansion for thermal changes and some for moisture changes.⁹ These figures are reasonably accurate but for non-homogeneous materials such as concrete, the range can be quite large. Formulae also have been established to approx-

imate creep and shrinkage but the response to chemical action is unpredictable.

Temperature/ Moisture Differentials

There are more than 20 different forces that can produce building movement, but the most significant are temperature and moisture changes that create volume changes. Figures are available for seasonal and diurnal ambient and dewpoint temperatures throughout the country, but these are not the only determining limits. Consideration must also be given to solar absorption, direct solar and reflected radiation, their rate of change and the heat storage capacity of building elements. Latta⁹ suggests that solar absorption would increase the ambient temperature by 100 times the coefficient of solar absorption, an approximate increase of 40 to 90F depending on the color of the surface. Cullen¹⁰ suggests that the ambient temperature be increased by 80F which correlates well with calculations for sol-air temperatures (S.A.T.) contained in the ASHRAE Handbook.¹¹

The length of the construction season is equally important and may be the major determining factor, since the roofing and cladding are often applied long before the building environmental controls are activated. During this period the frame will experience the largest temperature and moisture-induced changes, and the rate of response will closely approximate the rate of ambient temperature change without the damping influence of the completed cladding system.

Moisture Differentials

Volume changes in the structure, deck and cladding induced by moisture changes generally are not significant except in concrete. In wood beams the percent of change parallel to the grain is very small and can be ignored. In plywood decks the normal 1/4-inch joint required between sheets is sufficient to absorb inplaner movement.

The major significant moisture-induced change in cast-in-place concrete is shrinkage, which is non-reversible. Volume changes due to humidity gradients are not so critical because they are often offset by temperature changes. However, vapor released from concrete slabs and plaster during construction may condense on precast concrete elements and cause volume changes.

Fixity

Theoretically, the fixity of building elements can vary from near 0 to 100 percent, but, practically, the range is less. The degree of fixity can vary with the detail of the connections, which is a function of the design, and with the quality of workmanship, which is not. Moreover the fixity of a joint can be altered by corrosion, carbonation or other chemical action.

Stress Tolerance

The amount of stress members can absorb without deformation can be calculated, but the imposed stress can only be estimated from assumed temperature and moisture changes and the degree of fixity.

Risk

Since it is as unrealistic to design a structure for an infinite life as it is to design for zero probability of failure, a certain degree of risk must be accepted as inevitable. Therefore, the initial design decision must be to determine the desired service life of the building and the degree of risk that can be ac-

cepted. In determining the tolerable degree of risk the designer must consider:

- consequence of failure to life or property which must be quantified. Is the failure mode leaking, cracking, failure of major elements or just deterioration of finishes?
- quality of workmanship and site control considering such factors as overtightening bolts at sliding connections and the construction timetable.
- life span to cost relationship.

Any rational approach to determine spacing for cumulative movement must consider all the above factors.

LOCATION OF JOINTS FOR CUMULATIVE MOVEMENT

As previously mentioned, most of the authoritative references for spacing expansion joints in roofs to accommodate cumulative movement were promulgated prior to the oil embargo and subsequent increase of roof insulation. In light of this, published joint spacing needs to be re-examined.

Some of the more important factors that will dictate the need for these joints are:

- whether the deck is a self-insulating type;
- the period that the unclad frame will be exposed;
- the restrictions imposed by the wall cladding system.

Obviously a single arbitrary dimension cannot be valid for all buildings or all types of construction.

Insulating Decks

Many gypsum and lightweight insulating decks do not have additional insulation and are thus exposed to the full sol-air temperature range which can exceed 150F. In these cases the prudent designer would do well to conform to the deck manufacturer's suggested maximum spacing of 200 feet.

Frame Movement

In those cases where the structural frame will be exposed to both winter and summer temperatures prior to enclosure and activation of the mechanical systems, the effects of these extreme temperature ranges on the frame should be investigated. In symmetrically framed buildings the maximum thrust will be at the ends and approach zero at the center. This can be estimated using the sol-air temperature differential for the locale. The column stiffness and the base connection are one limiting factor. The capacity of the interior beams to absorb stress without distortion is the other. In the absence of a thorough analysis a conservative estimate of 50 percent - 75 percent fixity may be used depending on the tolerable risk and static redundancy.

Cladding Movement

Many early references required expansion joint spacings for roofs to be less than those required for walls. That is no longer valid for all roofs because, with well insulated roof decks, the deck and frame will not respond to ambient temperature changes to the same extent as the exterior walls. Moreover, since many walls are also better insulated, but on the inside, they are subject to even greater movement because they do not enjoy the tempering influence of the controlled interior environment, it follows that the capacity of the cladding to absorb cumulative movement will be

primary in determining the need for expansion joints.

The maximum practical width of an expansion joint in a wall will generally be the controlling factor. Columns without fixed-end bases can usually accept more displacement than the enclosing wall. With paired columns a joint in the structural frame can be made as large as required and the roof expansion joint can also be constructed to any width. On the other hand most wall joints are filled with a sealant whose practical maximum width is 2 to 3-inches. There are gaskets and mechanical joints available for wider joints but maintenance, cost and aesthetic considerations often preclude their widespread use. This limited movement capability may well be the controlling factor and perhaps spacing joints even closer than the roof deck or structure would require. Refer to Rainger⁷ and other sources for limits on maximum movements in cladding.

EXPANSION JOINTS AND MEMBRANE SPLITTING

If, based on the foregoing, the location of expansion joints is calculated to exceed the recommended 200 feet of spacing, will this result in membrane splitting? An analysis of the mechanics of splitting indicates that this is not the case.

Splitting can only occur when the stress capacity of the membrane is exceeded. Cullen¹² has shown that thermally induced movement is a factor in splitting failures, particularly in cold climates, but roofing technologists also have shown that a healthy, well-made membrane has the capacity to resist inplaner stresses imposed by the most extreme temperature changes providing it is uniformly attached to the substrate.

Excessive inplaner stresses can be generated where attachment is not uniform, such as over wide insulation joints, at joints where the insulation is insufficiently attached to the substrate or where interply moppings are inordinately thick. The length of the roof is not significant since length is not a factor in the equation to calculate temperature induced stress. Griffin⁶ suggests that total stress concentrations increase as the distance between expansion joints increases because of the greater movement potential. This may be a rational reason for dividing the roof into discrete areas but certainly no justification for using expansion joints for this sole purpose.

Expansion joints are complicated to construct, require maintenance, are subject to fatigue failure and, if properly designed using paired columns, are costly. Other equally effective methods can be employed to relieve stress concentrations.

Cullen¹³ recommended spot, channel or sprinkle mopping to provide stress distribution over greater areas. Mopping over punched base sheets assures a more uniform method of spot attachment. Mechanically attaching the insulation offers an even greater improvement to achieve a uniform attachment. Taping insulation joints also can be useful.

Almost 20 years ago Turenne¹⁴ suggested roof area dividers to limit the roof areas and anchor the insulation and membrane. These suggestions are still valid and less costly and complicated than expansion joints. They also serve the purpose of relieving stress concentrations at reentrant corners.

CONCLUSIONS

If it serves no other purpose this paper will at least show the complexities of spacing expansion joints, particularly those

to absorb cumulative movement. In view of the many complicating factors that have been mentioned it may be useful to conclude by briefly restating the more important considerations.

1. Wherever there are structural discontinuities of framing, materials or stiffness that can create differential movement, expansion joints are required to relieve stress concentrations.
2. With today's thermally efficient buildings, joint spacings to absorb cumulative movement can be increased substantially beyond 200 feet, with few exceptions. But each building must be evaluated individually.
3. Joint spacing will often be governed by cladding requirements and joint sealant capabilities rather than the structure or the deck.
4. Frames that are expected to be exposed for prolonged periods should be investigated for column bending and beam stresses using sol-air, not ambient, temperatures.
5. The degree of fixity and the amount of risk that can be accepted must be considered.
6. Providing expansion joints in the structure and deck of large rectangular roofs for the sole purpose of reducing membrane splitting cannot be justified. BUR splitting can be reduced by mechanically fastening the insulation, uniform spot attachments to the substrate and by using roof area dividers, a far better alternative than expansion joints.

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