SEAOSC SEMINAR

"DESIGN REVIEW & INSPECTION OF PRESTRESSED CONCRETE BUILDING PROJECTS"

This seminar will make the design engineer aware of the importance of adequately reviewing the plans and making field observations of prestressed and post-tensioned concrete building projects. It is the intent of this seminar to instruct the design engineer in the methods of checking and what to inspect on this type of project. Also to be presented will be a review of important code sections governing prestressed and post-tensioned concrete construction.

JANUARY 10 & 11, 1989

1) "Design Review - Asset or Liability? A Structural Engineer's perspective."
Does plancheck work on specialized structures such as prestressed concrete? What are the problems? What are the solutions?
Speaker: John A. "Trailer" Martin, Jr. S.E.

---

2) "Design review of post-tensioned concrete buildings - important code requirements"
What not to miss and what happens if you do? What not to worry about.
Speaker: Merrill R. Walstad, S.E.

JANUARY 17 & 18, 1989

3) "Shortening problems in post-tensioned concrete buildings."
How to address shortening problems and the relationship between Engineer and Planchecker in arriving at the solution. Problems that need judgement.
Speaker: Kenneth B. Bondy, S.E.

---

4) "Design review of precast prestressed buildings - Important code requirements."
What not to miss and what happens if you do? What not to worry about.
Speakers: Barrett T. Bunce, S.E.
David B. Prange, P.E.

JANUARY 24 & 25, 1989

5) "Inspection of post-tensioned concrete buildings."
What to look for - tolerances, qualifications of inspectors. What happens if you miss something?
Speakers: Manly L. Jackson, P.E.
Antonio S. "Tony" Luisoni, C.E., S.E.

---

6) "Inspection of precast prestressed concrete buildings."
What to look for - tolerances, qualifications of inspectors. What happens if you miss something?
Speakers: David A. Sheppard, S.E.
Richard L. Hegle, S.E.

SEAOSC
2550 Beverly Blvd.
Los Angeles, CA 90057-1092

SHORTENING PROBLEMS IN POST-TENSIONED CONCRETE

- *Ken Bondy, S.E.*

Introduction

Cracking caused by restraint to shortening (RTS) is the biggest problem associated with post-tensioned building structures. Other design considerations like member sizing, material quantities, code conformance, etc., are relatively easy to solve because they lend themselves to direct numerical solutions. Further, highly efficient and accurate computer programs have been developed which rapidly do all these things for you. But no computer program, nor direct numerical method, has yet been developed to solve the shortening problem.

The reason for this is that restraint-to-shortening (RTS) problems and solutions cannot be quantified by equations. The time-dependent mechanics of volume change in post-tensioned buildings is exceptionally complex, requiring an empirical, rather than a numerical solution. The solution to RTS problems is a technique, implemented by joinery details, rather than a number. Thus experience and judgment are the prime, and to date, only attributes for solving shortening problems.

RTS cracking first became apparent as a potentially serious problem in post-tensioned buildings in the early sixties, when the first PT buildings were several years old. Recognizing the problem, designers began trying various solutions on subsequent buildings. They observed the effectiveness of their solutions in the behavior of the buildings. Details which were effective continued to be used and improved, those which proved ineffective or grossly expensive were discarded. Thus a large database of experience with the behavior of post-tensioned buildings began to be formed, one which has been growing now for some 25 years. Out of this base of experience, now covering thousands of PT buildings, evolved the techniques in use today to solve shortening problems.

While most effective solutions to RTS problems tend to be similar, experienced engineers will vary in their individual approaches. Using somewhat different details and approaches, competent PT designers nonetheless consistently produce quality PT buildings. This is not surprising given the subjective nature of RTS solutions. Thus there exists a collection, or "band" of techniques which can be called "acceptable" or "standard practice" or "state-of-the-art" for solving shortening problems. The purpose of this paper is to aid the plan reviewer in determining if a solution presented falls within the band of techniques which currently make up the "state-of-the art". The job of the plan reviewer is not to dictate a particular shortening solution, but to ensure that one is presented which falls within the spectrum of what is considered acceptable, one which has "worked" in the past.

And finally a word about the goal of RTS solutions. With almost 100 years of experience now with reinforced concrete structures, we can reliably generalize that "all concrete buildings crack." They do, and some more than others. While it is very difficult to quantify, most experienced concrete engineers can inspect a concrete building and determine if the cracking observed is "normal", or if the building compares favorably with most other concrete buildings in the area. The goal of RTS solutions in post-tensioned concrete buildings is not to produce a crack-free building. To the best of my knowledge, that is not possible. Further, there is no economic or structural reason that post-tensioned concrete buildings must exceed the standards which we have come to accept for other types of concrete buildings. Thus the goal of the designer is to <u>minimize</u> cracking and produce a building which would, by all standards, be considered <u>acceptable</u> for concrete buildings in general. Having done that, the design can be considered successful.

What's the Problem?

The problem is not that PT buildings shorten that much more than non-prestressed concrete buildings but that they shorten in a different way. Shrinkage is the biggest contributor to shortening in both prestressed and non-prestressed concrete. In prestressed concrete, elastic shortening and creep add only about 15% to the total shortening. So total shortening is not drastically different for prestressed or reinforced concrete. The reason that shortening is a big problem in post-tensioned concrete, and it isn't in non-prestressed concrete, lies in the manner in which they each shorten.

Assume two concrete slabs each cast exactly 100' square, one of reinforced concrete, one of post-tensioned concrete stressed to normal compression levels (150-200psi). Ignore the extra 15% contributed by elastic shortening and creep in the PT slab and say they both try to shorten, with time, about 1" in each direction. As the RC slab tries to shorten, movement is resisted internally by the bonded reinforcing steel. The rebar is put into compression and the concrete in tension. As the concrete tension builds up the slab will crack at fairly regular intervals. The ends of the slab stay in the same position in which they were cast (the overall dimension of the slab remains 100'). The concrete DOES become

1" shorter, but not in overall dimension, rather in the sum total of the many cracks which occur across the slab, their combined widths totalling one inch. The rebar tends to distribute the inch of shortening throughout the length of the slab in numerous cracks, each small enough to be considered acceptable. Thus RC tends to solve its own shortening problem internally by the creation, essentially, of hundreds of small "expansion joints" in the form of shrinkage cracks distributed throughout its length. Restraint forces in connected elements, walls and columns, tend to be negligible since the "relief" has been provided through cracking in the slab itself. The slab, as we say, gets "soft" relative to connected elements.

Not so with the PT slab. Its principal reinforcement is the unbonded post-tensioning. Much less unstressed steel is present and consequently much less restraint to the shortening is provided internally. Shrinkage cracks which form are closed by the post-tensioning force. Lacking the means for distributing its required 1" of shortening in the form of numerous shrinkage cracks, the PT slab DOES become 1" shorter, half at each end. Unlike the "soft" RC slab, the active movement of the PT slab generates large restraining forces in the connecting walls and columns, particularly at the ends of the PT slab where the movement is greatest. These restraint forces, if large enough, can produce severe, concentrated cracking in the slab, walls, or columns at the extremities of the slab.

The Consequences of RTS Cracking

RTS cracking has considerable cosmetic and serviceability consequences which have played a part in much of the litigation dealing with post-tensioned buildings over the last 25 years. RTS cracks are often wide and unsightly, due to the large forces involved and their concentrated nature. Aside from their appearance, the most serious consequence of RTS cracking is leakage.

The good news, such as it is, is that restraint to shortening cracking has had no measurable effect on the strength of post-tensioned members. Nor does it significantly change the strength of attached members such as columns or walls. RTS cracks occur early in the life of a structure (most, to my knowledge, in the first 3 months), quickly reach a maximum width, and do not increase in number or severity with time.

Factors and Solutions Influencing RTS Cracking

Two major factors influence the presence and severity of RTS cracks, concrete length and restraint conditions. Important secondary factors include floor level in multistory buildings, prestress compression level, and the shape of the post-tensioned slab. Obviously they are all related but, to some degree, they can be isolated and addressed separately.

All solutions to restraint problems in post-tensioned buildings in one way or another involve eliminating the restraint by separating the slab from the restraining element. The separation should be permanent if possible, with consideration to other factors such as vertical slab support and lateral shear transfer. If a permanent separation is not possible, cracking can be mitigated to an acceptable level by using temporary separations which allow enough of the shortening to occur before the connection is made, such that cracking cause by the remaining shortening is not offensive.

All other factors being equal, RTS cracking tends to be proportional to initial pour size. All elements of a monolithic piece of post-tensioned concrete will shorten towards its center of mass, a point normally close to its geometric center. This center of shortening does not move as the concrete shortens, while all other points move towards it. The farther from the center of shortening, the more the movement. The smaller the concrete mass, or pour size, the smaller will be the movement due to shortening. Some general guidelines have evolved regarding concrete length, and they are as follows: 1) the maximum <u>permanent</u> length of any post-tensioned building (either the total length of the building or the length between expansion joints) is 300 feet; 2) the maximum <u>temporary</u> length of any monolithic pour in a PT building is 150 feet (200 feet if restraint is minimal). The temporary length is maintained between pieces of the building by the use of a physical separation between two sections of deck. The length of time required to separate the two slab sections is a function of the restraint conditions and will be discussed later.

Restraint conditions are the second major factor affecting RTS cracking. They are a function of the stiffness of the restraining elements and their location in the structure. Isolated concrete columns provide relatively little restraint to shortening and rarely produce cracking in post-tensioned members. However, relative deformation between the tops and bottoms of columns can crack the column itself in certain conditions. Two conditions deserve special attention, edge columns with building dimensions greater than 200 feet and interior columns between ramps in sloping floor parking structures. To mitigate cracks in each of these conditions the columns should have near-ductile ties, at least #4 at 4" maximum spacings. Longitudinal column reinforcement appears to have little or no effect on column cracking in either of these two conditions.

Structural walls, concrete or masonry, present the ultimate restraint problem, obviously because of their much greater strong direction stiffness. By the way, restraint provided by the weak axis of the wall is negligible and thus shortening perpendicular to the long axis of the wall presents no problem. Wall problems are a function of their length, number, and location in the building footprint. Specific solutions to wall RTS problems are a function of the length of individual walls and differ in the cases of long, continuous ones such as perimeter basement walls, and shorter isolated ones such as shear walls. The border between long and short walls is about 60 feet. Restraint from long walls is generally relieved by a joinery detail which allows the slab to move relative to the wall, either permanently or temporarily. This detail must address not only the movement of the slab parallel to the long axis of the wall but other requirements of the wall such as bearing and lateral shear transfer.

RTS solutions for shorter, isolated walls depend on where they are in the building. Ideally, shearwalls should be centrally located abeam the center of shortening in each direction (see Figure 1). If this is done, and every effort should be extended to assure that it is done in the design process, shortening movement is small at the walls and monolithic connections may be used with no special joinery separations. On the other hand, very undesirable shearwall locations are shown in Figure 2 where the walls are located some distance apart, pulling against each other from the points of maximum slab movement. This condition begins to arise when the walls are separated from each other by about 60' and worsens as the distance increases. If undesirable shearwall locations are unavoidable architecturally, shortening cracking can be mitigated by providing separation details in the slab which temporarily isolate the offending walls. Normally, monolithic slab/wall connection details are used with shearwalls.

A special problem area exists at building corners where perimeter basement walls intersect. Because of the "two-way" shortening action of the slab in this area, cracking in both slab and walls can be particularly severe (See Figure 3). In this case details must be provided which allow the slab to move relative to the walls for as great a distance as possible from the corner, and in no case less than 20 feet. The separation detail should be permanent if at all possible. If other structural considerations preclude a permanent separation, temporary separations may be used with some compromise in crack mitigation. With short separation lengths, in many cases the cracking is merely moved inboard from the corner to the end of the separation detail, however even in that case the severity of the cracks can be greatly reduced (Figure 4). A good technique in "box" buildings with enclosing perimeter walls is to determine the absolute minimum length of shearwall required on all four sides, centrally locate them, and free the rest (Figure 5).

The floor level in multi-story buildings is an important secondary consideration in shortening considerations. Shortening problems rarely occur above the first supported level in multistory PT buildings. The reason for this can be deduced from Figure 6. Above the first supported level the floors tend to shorten uniformly and produce less and less relative deformation between the tops and bottoms of the vertical elements as the story level increases. The foundation, however, tends to stay put and thus relative deformations are a maximum in the first lift. That is why the most conservative shortening solutions must be applied at the first supported level of multistory buildings, but can be relaxed on upper floors as the building gets "soft" with height.

High prestress compression levels aggravate, rather than alleviate, shortening problems and should be avoided. Any extensive portion of a post-tensioned deck with compression levels above 200 psi should be considered a "red flag" signalling shortening problems and dealt with accordingly. Proportion post-tensioned members such that compression levels above 200 psi are not necessary. You'll save money and stay out of court.

Finally, the shape of the post-tensioned floor system can influence shortening cracks. All corners, bends, and openings are "stress concentrators" which attract cracks. This type of cracking can be minimized by the proper amount and location of reinforcing steel at the "hot spots" which "cut off" the crack at the point where it tries to start (at the corners, for example) and distribute it as a series of small cracks rather than one big nasty one. Examples of this type of cracking, and the reinforcing used to minimize it, are shown in Figure 7.

The Specific Details Used to Solve Shortening Problems

A group of separation details have survived the test of time and have become somewhat "standard" in solving shortening problems. They present a good balance between effectiveness, ease of construction, and economics. These details are presented in this section. Certainly other details and materials can do the job but these are the ones most commonly used.

There are two general types of separation details, permanent and temporary. In the permanent type, the separation is maintained for the life of the structure. In the temporary detail, the separation is maintained for a specified period of time, and then a solid connection is made between the structural elements.

Permanent separation details are shown in Figures 8-10. Figure 8 can, of course, only be used if the wall is not required for vertical slab support (i.e., the slab can cantilever to the wall. In all three of these details, the slab can be used as a "support", or reaction, for the wall spanning vertically under the action of soil pressure. All three details can be used with concrete or masonry walls. Note that none of the details provide shear transfer capability parallel to the wall, although Figure 10 does supply some "tie" between the slab and the wall in the event of very large relative deformations.

Figures 11-15 show temporary separation details. Figures 11 and 12 are "pourstrips", 11 separates slab and wall, 12 separates two sections of slab. Note the shoring required to support the edges of the post-tensioned slabs until the pourstrip is poured and up to strength. The pourstrip reinforcement is designed for the full continuity moment and shear. Figure 13 is a knit-strip detail used at the tops of concrete walls. Figures 14 and 15 can be used with either concrete or masonry walls. Note in these two details that the shear transfer provided by the sleeved dowel is by bolt action only. In Figures 14 and 15 the separation between the wall and slab can be accomplished with two layers of heavy felt paper in lieu of the masonite, however this requires an extremely smooth surface at the top of the wall to avoid "keying" between slab and wall.

Finally, one last detail deserves attention. I recommend that all post-tensioned slabs contain a continuous, developed mat of reinforcing steel in both directions, which is in addition to all other bars required for any other reason. Normally I use #4 @ 36" o/c ew as a minimum, increasing this to #4 @24" in "red-flag" shortening situations (long dimensions, lots of stiff walls, etc.) This continuous mat is in addition to the "hot-spot" corner bars mentioned in the above section. This mat of bars has proven to be effective in minimizing all forms of shortening cracks and is highly recommended. Continuous support bars for tendons may be used to satisfy this requirement so long as they are adequately developed.

How Much Time?

The time period in which temporary separation details are to be left "open", or "free", is critical to the success of the detail. Simply stated, the detail must be left open long enough so the the remaining shortening does not result in excessive cracking. Some understanding of the basic time-dependent volume change behavior in PT concrete is necessary to understand how much time is necessary.

The relationship between volume change (let's just call it "shortening") and time in PT structures is shown in Figure 16, reproduced from the PTI Post-Tensioning Manual. One can find this type of curve in many references but they are all similar. It is understood that the curve is affected to some degree by concrete properties, climatic conditions and curing techniques. It is the <u>shape</u> of the curve which is pertinent, not the precise values.

Note that the horizontal **TIME** axis is logarithmic, and that the rate of shortening reduces <u>drastically</u> with time. About half the total shortening to ever occur in the member occurs in the first two months; the remaining half takes about 20 years. It is substantially for this fact that temporary shortening details work.

The forces generated in restraining elements are not only a function of how <u>much</u> shortening occurs, but how fast it occurs. A half inch of shortening applied instantaneously to the top of a wall or column will generate roughly twice the restraining force as will the same half-inch applied slowly over a period of five years. This is due to an inelastic creep behavior common to materials known as "plastic flow". Thus the designer can mitigate cracking in two ways by temporarily preventing restraint: 1) eliminating restraint forces from that portion of total shortening which occurs in the "open" time period , and 2) minimizing cracking caused by subsequent restraint forces after the detail is "closed" because of the much slower rate of shortening.

So how much time is needed? Shortening details closed in less than one month are probably a waste of time, effort, and money. For average restraint conditions (modest lengths, walls relatively centered, above the first supported floor, etc.) a 30-day separation is considered adequate. For more severe shortening conditions (long perimeter walls, shearwalls pulling against one another from distances substantially over 60 feet, exceptionally large pour sizes, etc.), a two-month separation is in order. Note that the two-month separation, by most shortening curves, gets rid of about half the total shortening. This is an appealing firgure, and whether the 50% value is correct or not, the 60-day separation seems to do the job in these situations. For those days when everything is ganging up on you (big pours, lotsa walls, complex shape), just before you blow the whistle and assault the architect, use a 3-month separation. I have never seen temporary separations specified for longer than 90 days and longer periods are not really necessary. Anything which needs a separation longer than 90 days needs an expansion joint or shouldn't be built.

Summary

We have discussed the theoretical and practical aspects of solving shortening problems from the perspective of the plan reviewer. Guidelines have been presented which define the general areas of concern and influence in shortening problems, and the specific details used to solve them. Using these principles, the plan reviewer should be able to determine the nature of the shortening problems, if any, and to recognize if the proposed solution falls within normally accepted "standard practice" which has been successful on previous structures.

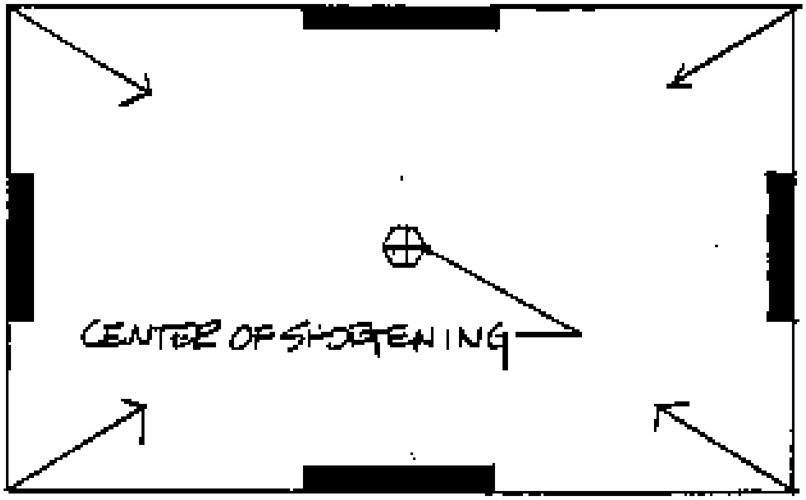


FIGURE 1

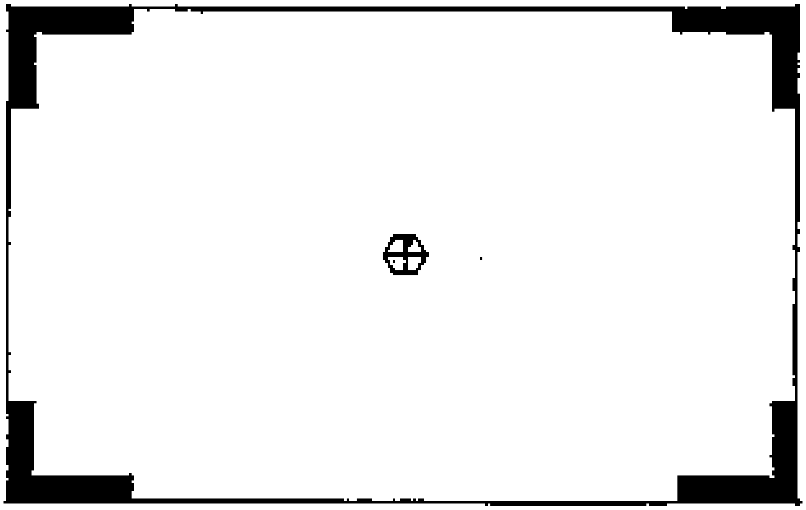
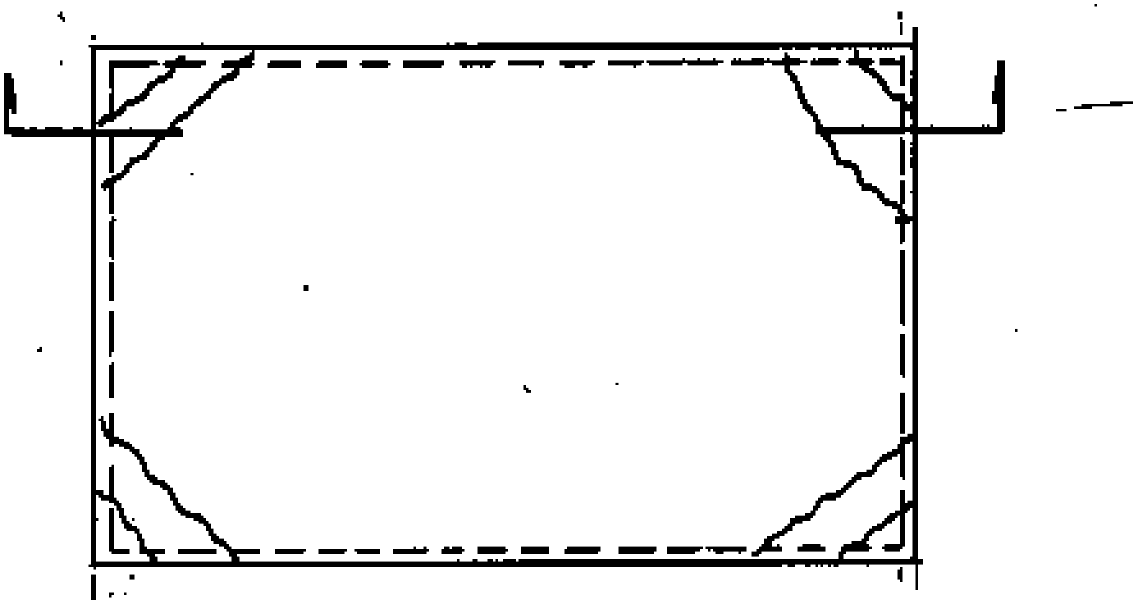
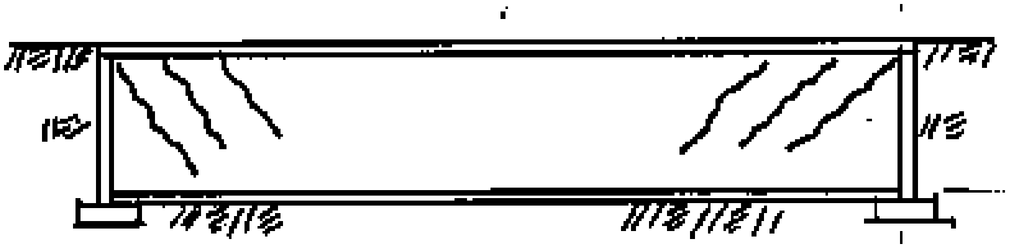


FIGURE 2

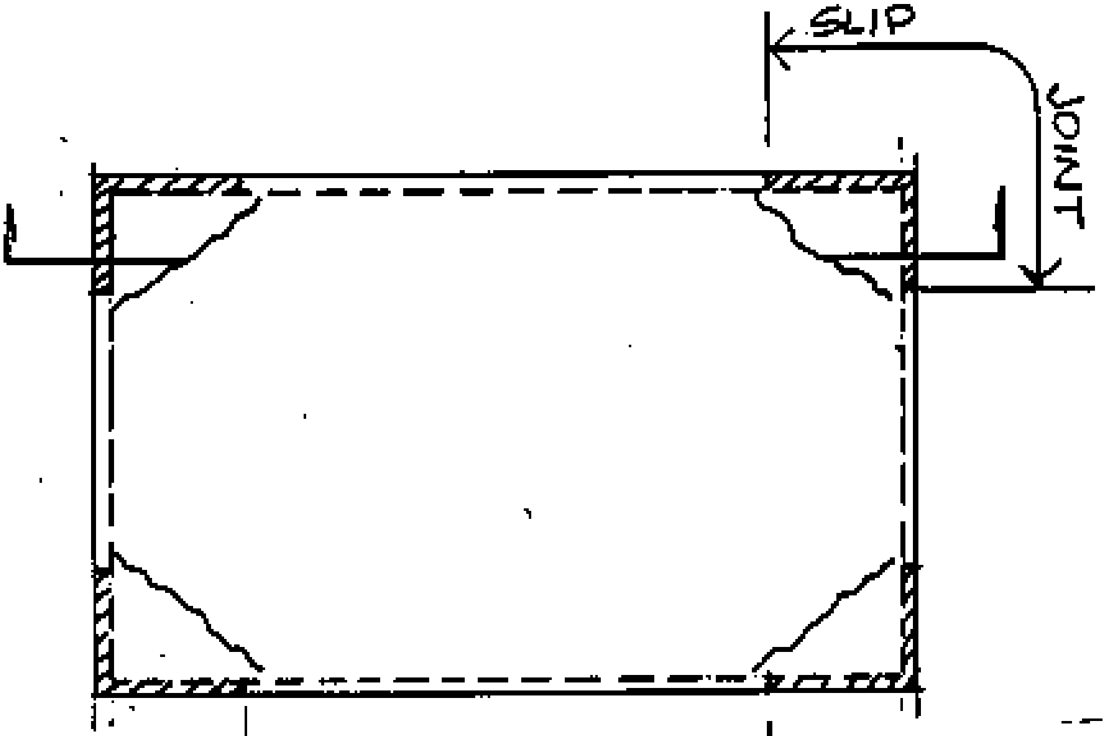


PLAN

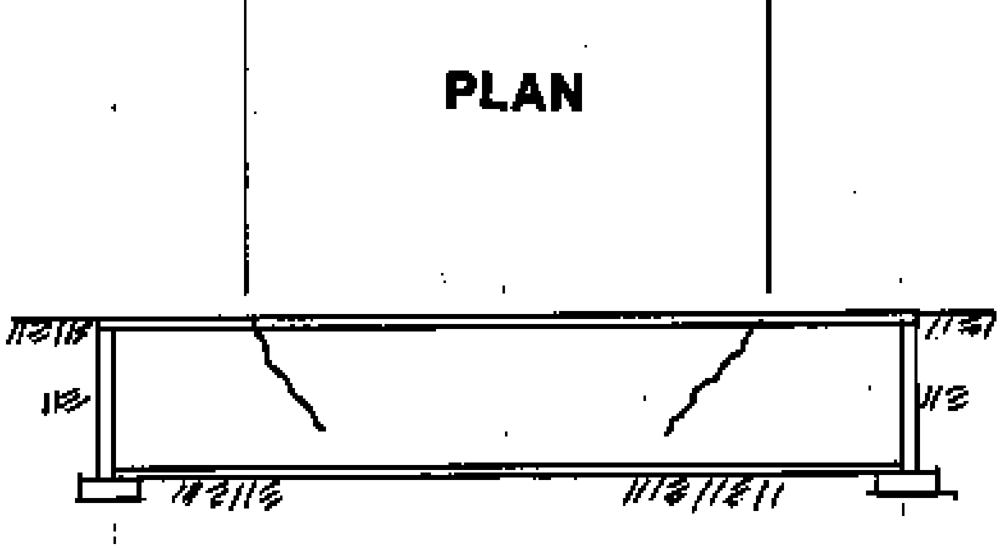


SECTION

FIGURE 3

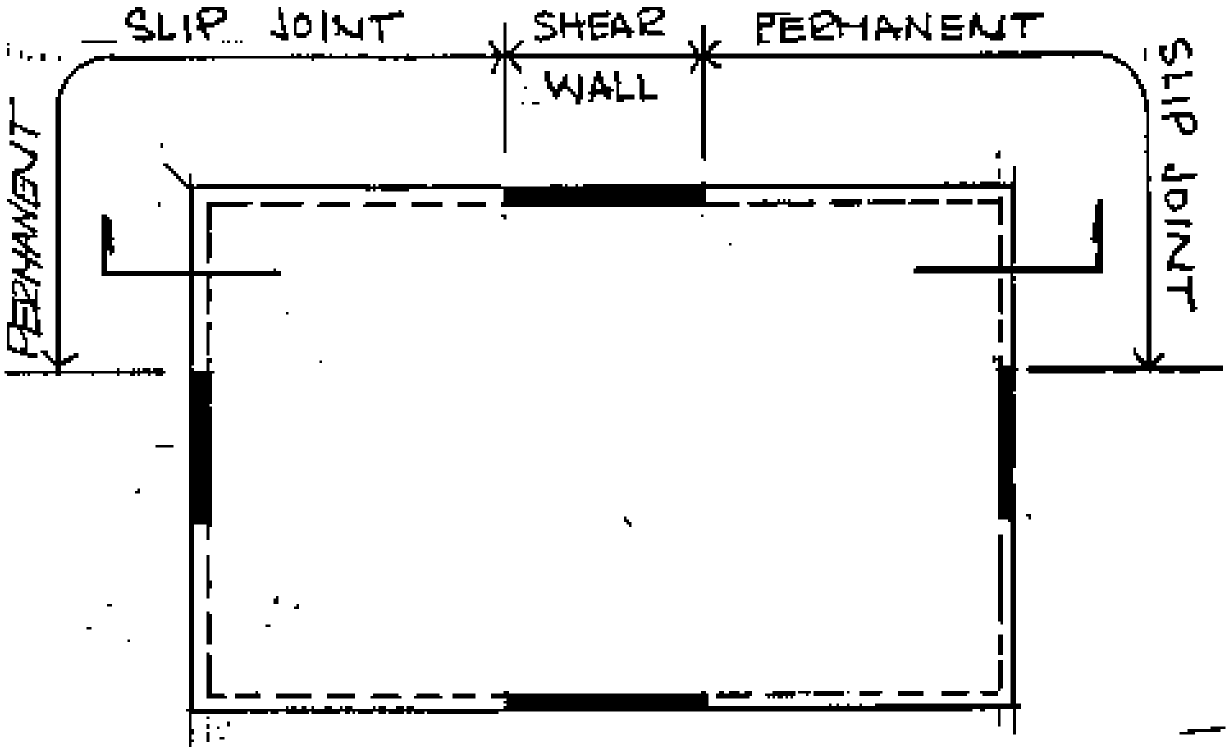


PLAN

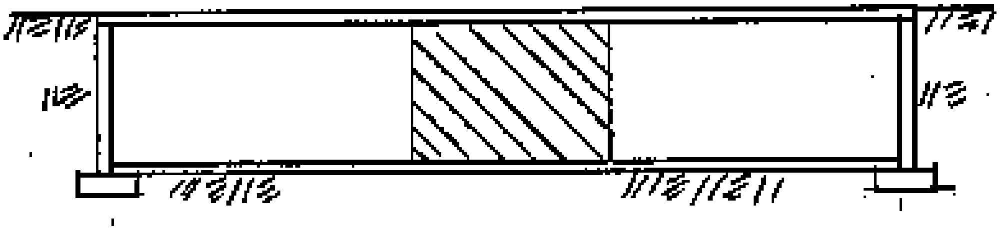


SECTION

FIGURE 4



PLAN



SECTION

FIGURE 5

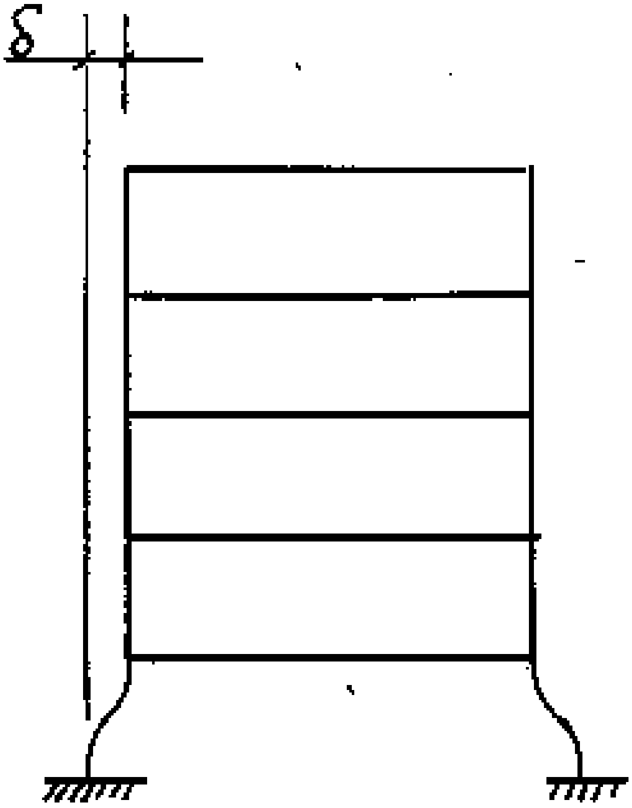


FIGURE 6

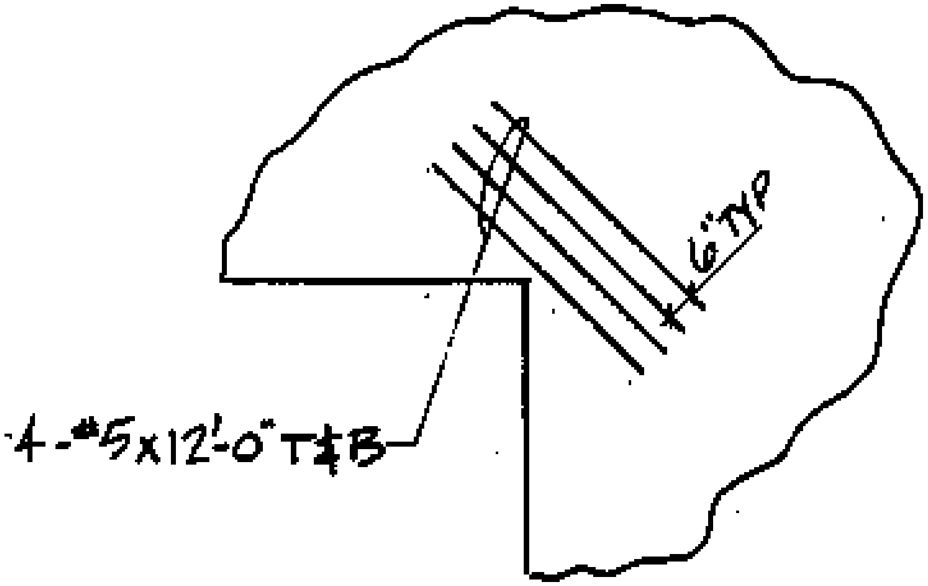


FIGURE 7

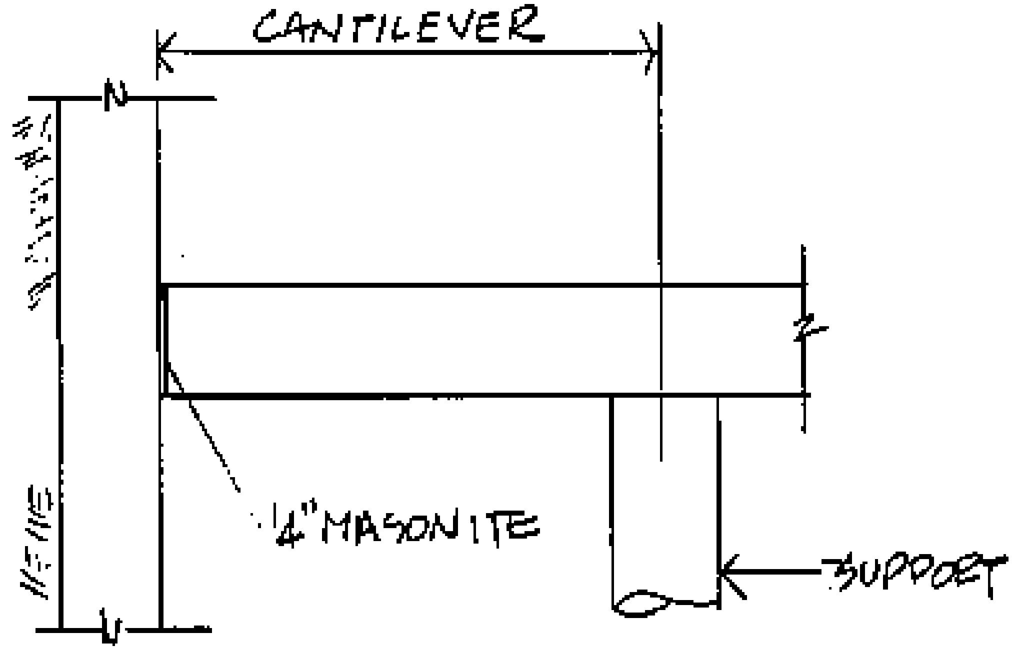


FIGURE 8 - PERMANENT SLIP JOINT

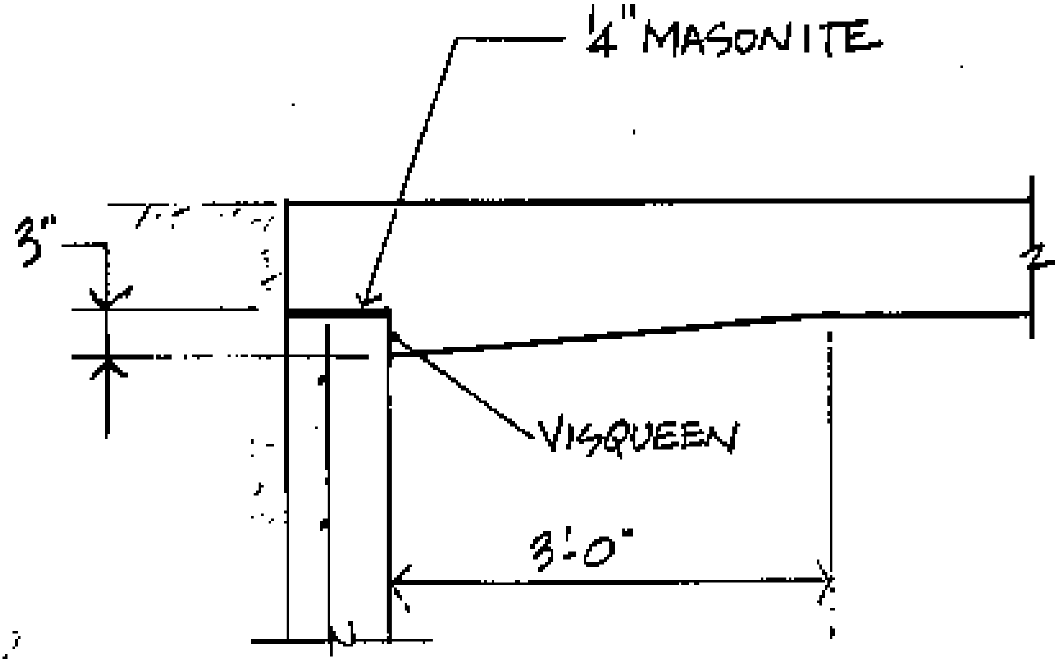


FIGURE 9 - PERMANENT SLIP JOINT

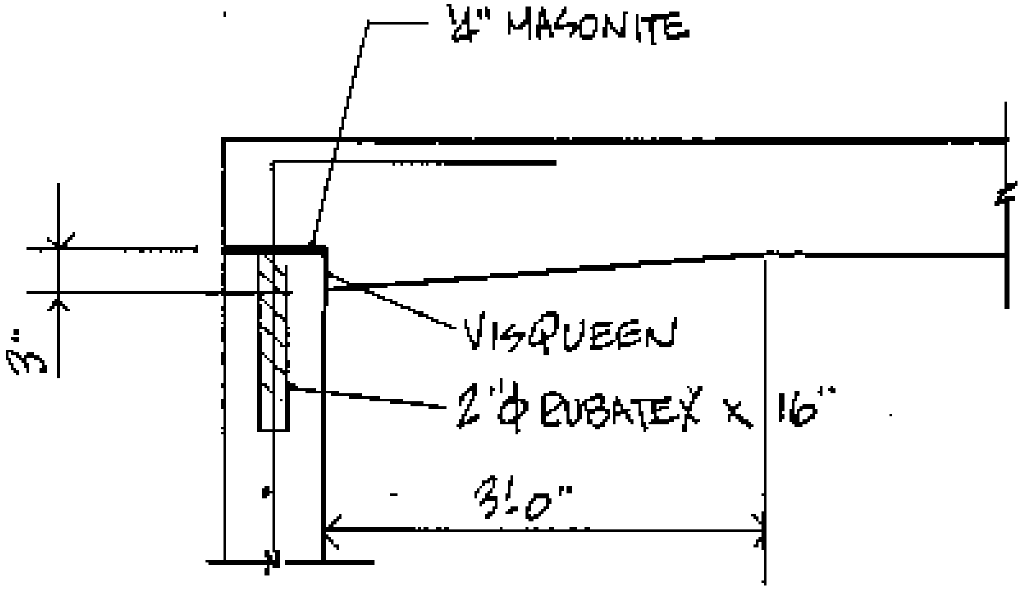


FIGURE 10 - PERMANENT SLIP JOINT

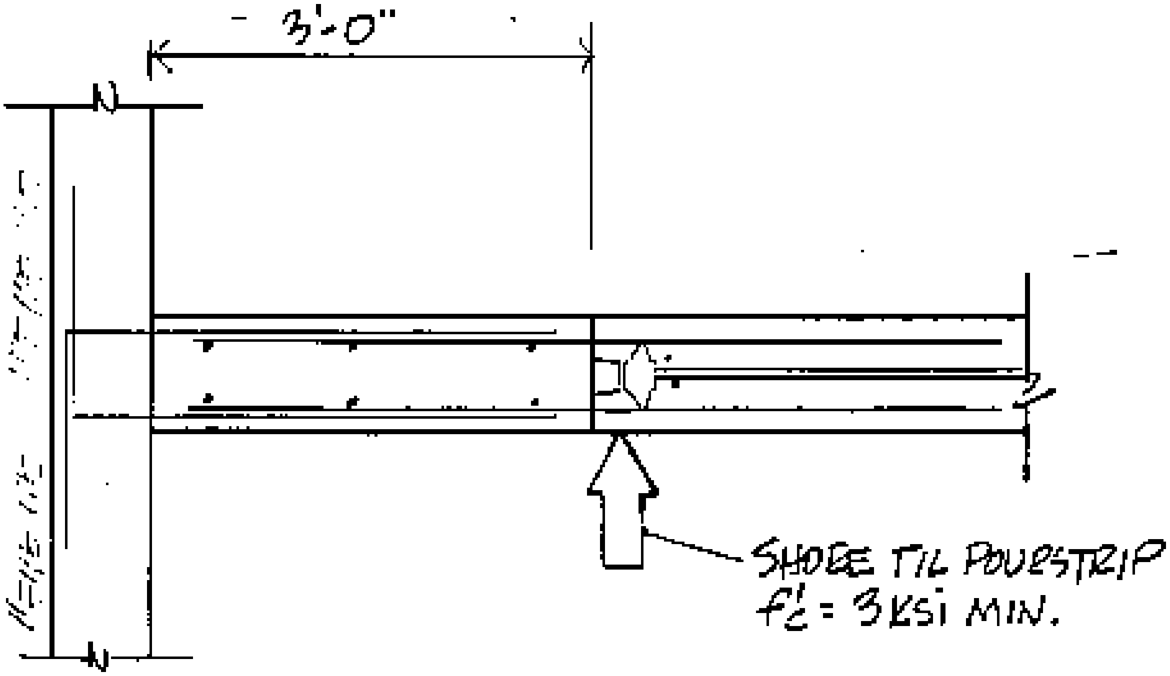


FIGURE 11 - POUR STRIP

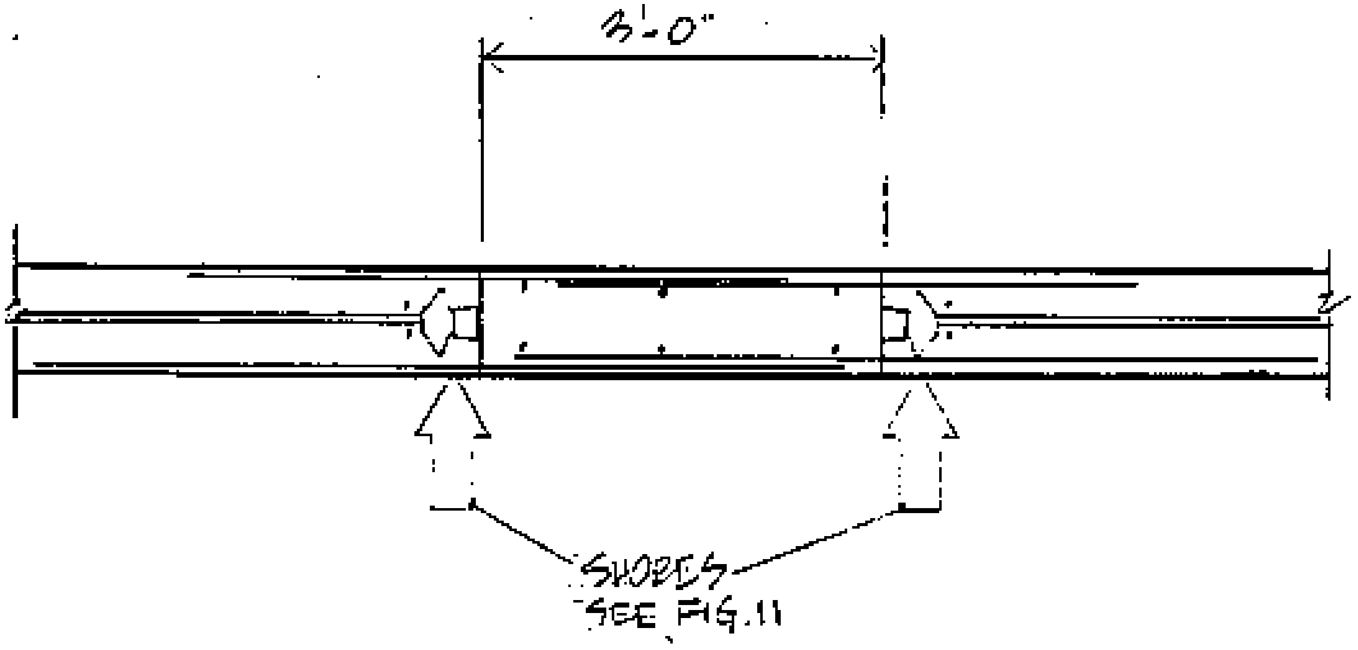


FIGURE 12 - POUR STRIP

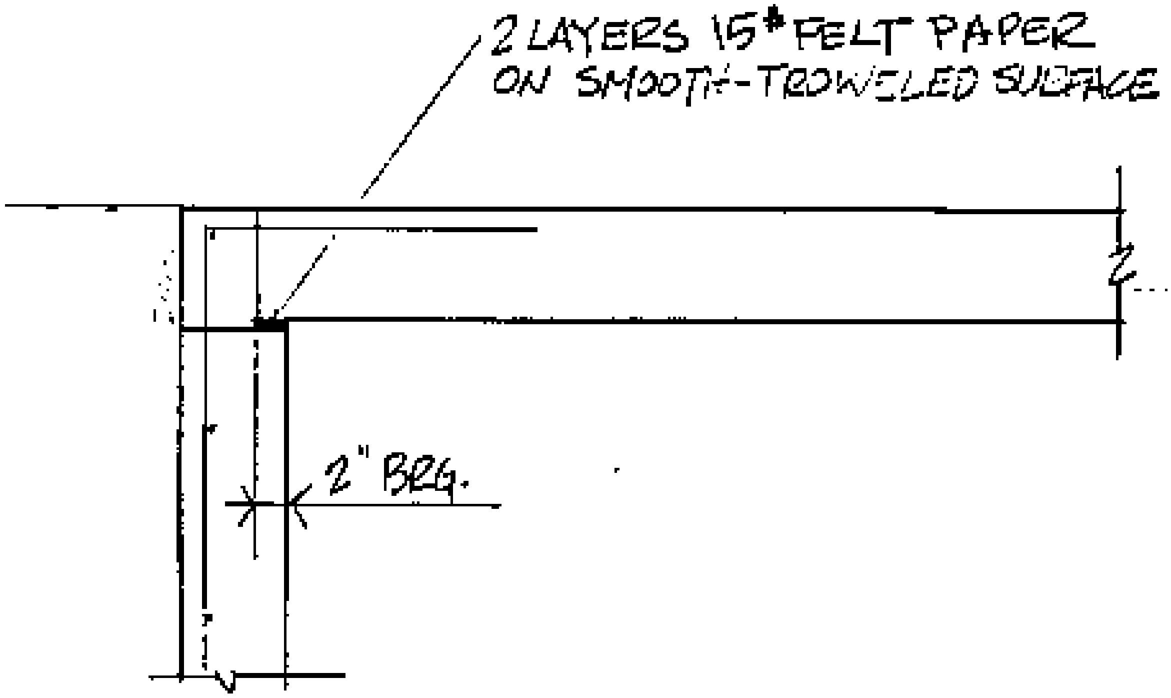


FIGURE 13 - TEMPORARY SLIP JOINT

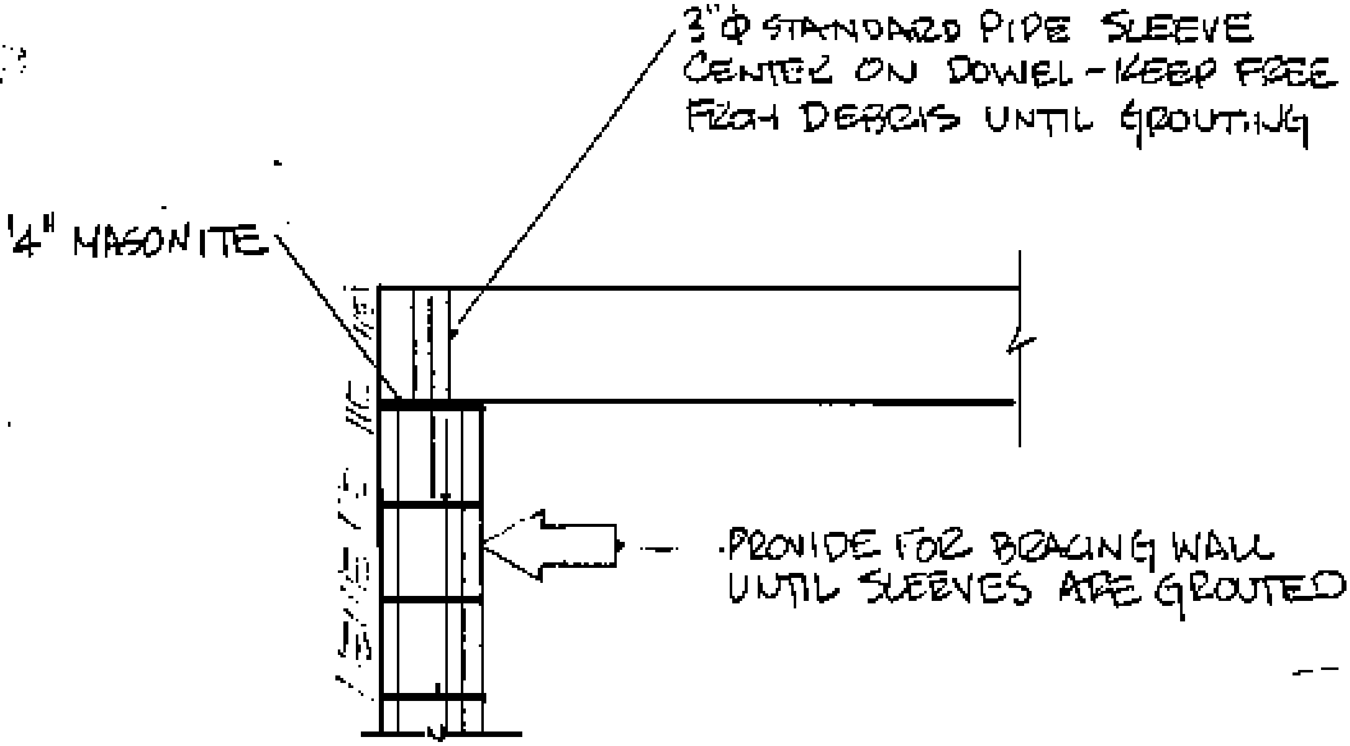


FIGURE 14 - TEMPORARY SLIP JOINT

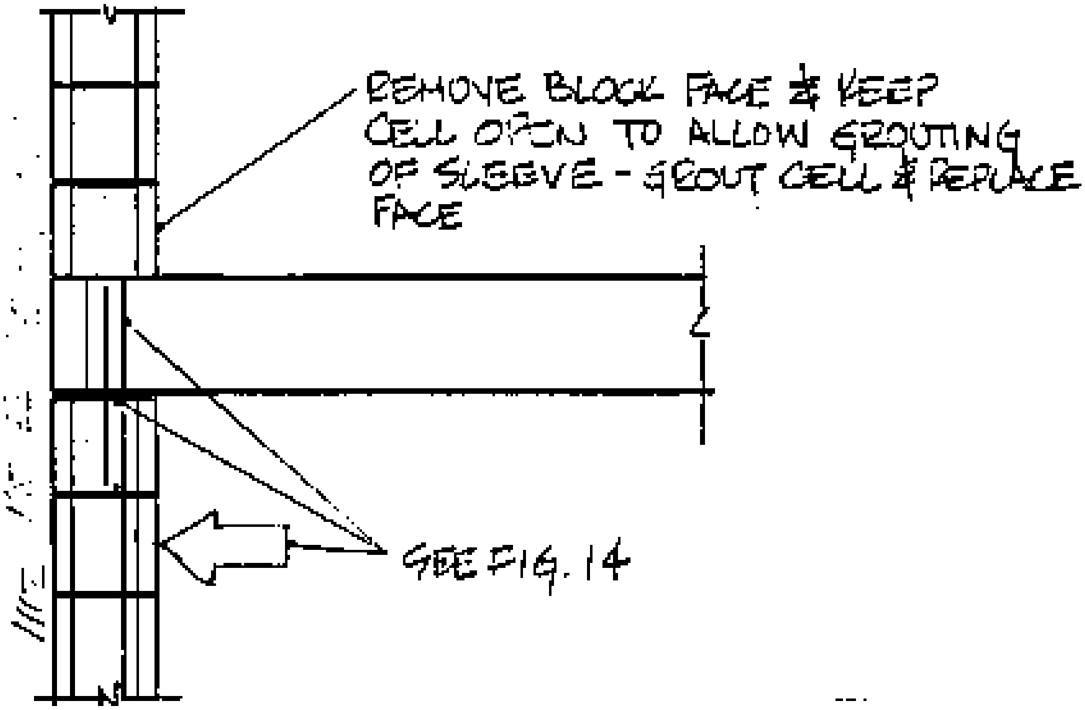


FIGURE 15 - TEMPORARY SLIP JOINT

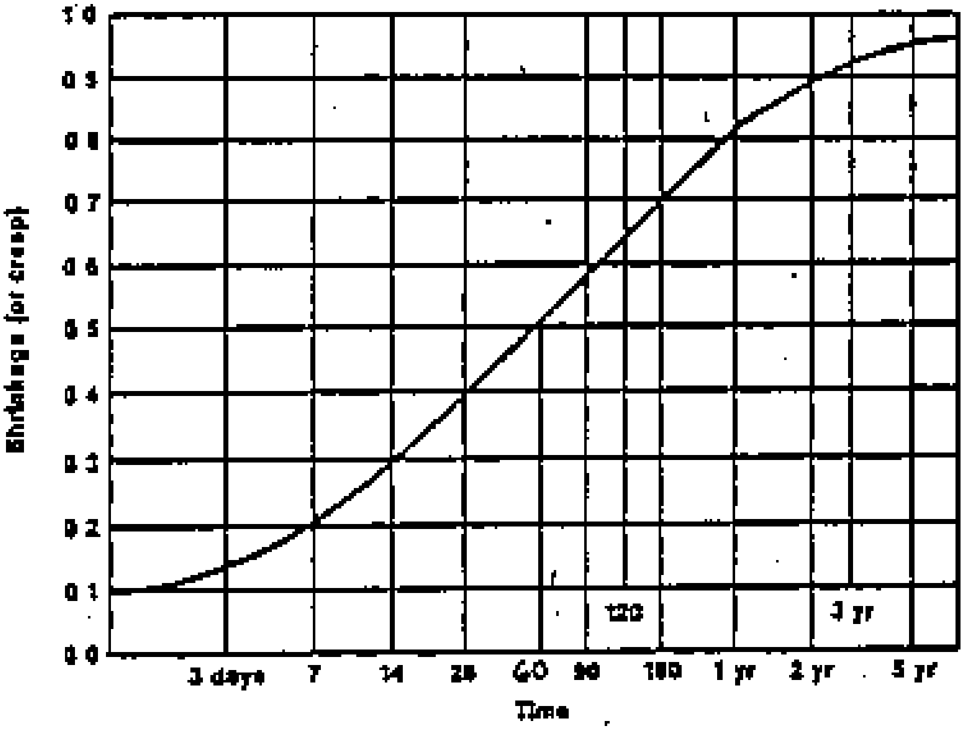


Fig. 16 — Approximate proportion of final shrinkage or creep vs. time

FIGURE 16