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A NOTE ON THE EARTHQUAKE PERFORMANCE OF REINFORCED CONCRETE SHEAR WALLS

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A great many one and two story buildings as well as many buildings as tall as 10 stories or higher have cast in situ reinforced concrete walls designed to act as shear walls for resisting seismic forces. Allowable design stresses in reinforced concrete shear walls have been increased in recent years in many building codes, although in one major code they have been drastically reduced. Concurrently, modern architectural trends have often resulted in the reduction of certain reserve strength features neglected in seismic design such as "non-structural" panel walls of brick or of reinforced concrete since these elements are often replaced by glass or by insulated metal panels. This, in effect, results in greater applied seismic forces on the shear walls. The frequent elimination of deep spandrel beams in favor of thin slabs which may meet glass or metal walls also tends to increase stresses in the shear walls since the strength and stiffness of the spandrels were often neglected when interior shear walls existed. In summary, it has been the experience in the United States and in many other countries in the world that the effective factor of safety in reinforced concrete shear walled structures has often been substantially reduced for seismic loadings. In many cases, inadequate methods of analysis have neglected critical stresses at boundaries and openings.

The state of the art of practical design of reinforced concrete shear walls was summarized in connection with the collapse of the Four Seasons Apartment House in the 1964 Alaskan earthquake.[1] An increasing body of literature is responding to the need for a better understanding of the nature and distribution of stresses in shear walls under seismic loadings.

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[1] "The Prince William Sound, Alaska, Earthquake of 1964 and Aftershocks", Vol. 2, Part A, pp. 191/192. (U.S. Department of Commerce, ESSA)

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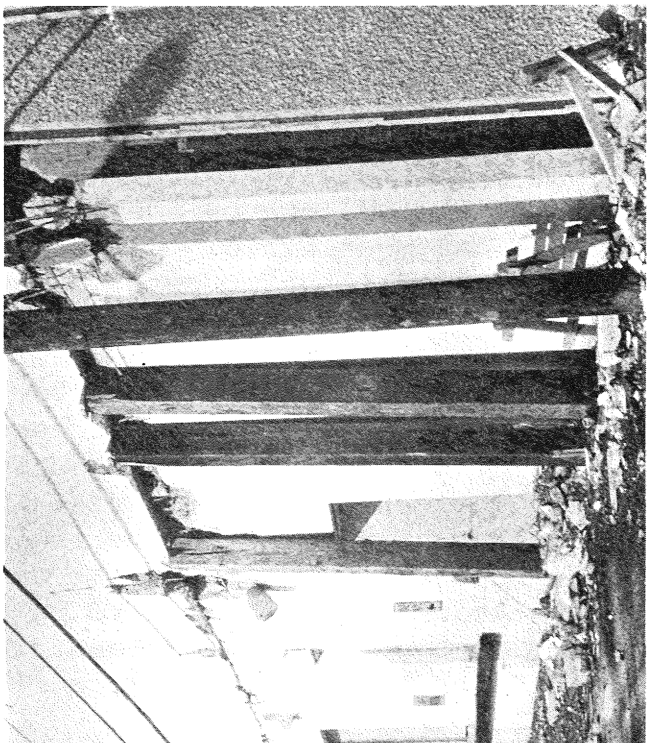
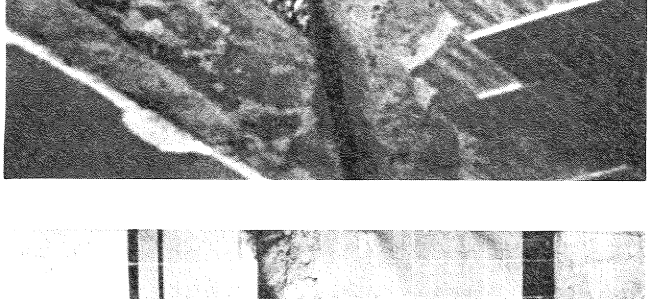
The structural engineer who must design and supervise the construction of today's buildings would do well to critically review local construction methods to be sure that his increasingly sophisticated mathematical design based on the assumption of monolithic cast in situ reinforced concrete is indeed a monolithic concrete.

Construction practice intended to insure monolithic concrete varies throughout the world. It has been the author's experience in most countries, including much of the United States, that the practice in this regard could stand substantial improvement. It has been the slippage along the contact faces of construction joints during earthquakes that has lead to, or contributed to, substantial damage in the building and sometimes to collapse. When a construction joint moves during an earthquake, the stresses in the other seismic resisting elements or structurally related elements often deviate greatly from those computed by the designer. This may lead to unexpectedly high stresses or failures elsewhere.

Figures 1 and 2 show construction joint movement in a major shear wall in the two story West Anchorage High School during the 1964 Alaskan earthquake. The joint was so smooth that some persons called it a "troweled joint". Figure 3 shows the movement in a poorly built construction joint in the rear of the Cordova Building after the 1964 Alaskan earthquake. The aggregate in this instance acted as "ball bearings". Figure 4 clearly indicates the construction joint slippage that occurred in a wall of the Penney Building during the same shock. The authors' files contain similar examples from many other earthquakes.

Construction practice in many areas is not far different from that shown in Figures 1 through 4. Concrete walls are usually poured to a convenient height which is dictated by floor or roof lines, wall openings, architectural requirements or the like. A white chalky material known as laitance rises to the surface of the freshly poured concrete wall. Laitance is of low structural strength and may provide a smooth surface which is difficult to bond to for subsequently placed concrete. In other words, the construction joint becomes a weak plane which has only the dowel action of the vertical reinforcing steel to hold the sections of the wall together. (It is somewhat unreal to calculate or to rely on the frictional resistance along smooth construction joints since large seismic vertical and/or over-turning forces often exist concurrently with horizontal forces, though building codes normally ignore vertical forces.)





Practice varies in construction joint preparation. Sometimes the surface is roughened as the concrete hardens, thereby providing a mechanical bond between the two pours. This represents a substantial improvement over that shown in Figures 1 and 2. The roughened surface may be adequate in many cases, but the concrete is still not monolithic. Cores cut for testing purposes at these joints often fall apart before testing.

In the authors' opinion, best current practice in California requires the use of mechanical bond through serrated shear keys plus the best possible contact between the freshly roughened surface of previously poured concrete using grout on the contact plane. Theoretically, if a freshly roughened surface with adequate grout can be furnished in the field, the mechanical bond should not be necessary. However, the almost universal experience is that workmanship is too lax to rely on adequate adhesion at the contact surface, so the mechanical key, such as illustrated in Figure 5 (or the equivalent), must be provided as an insurance factor.

The minimum requirement for adhesion usually calls for the removal of the laitance plus some roughening of the surface. Three procedures for improving adhesion are commonly acceptable in areas following best practices, although equivalent procedures exist. A summary of these three procedures are:

1. Sand blasting. Sand blasting has become increasingly popular in some areas since air compressors are becoming more frequently available on construction sites. Additionally, sand blasting also cleans the exposed steel. Lastly, workmen with slow and lazy habits do not create conditions that can not be easily corrected. The sand blasting process should be continued until the entire contact surface is clean and it has exposed the aggregate which is solidly embedded in the mortar matrix. The resulting sand must be cleaned out before placing the new concrete.

2. Chipping. Laitance removal may be performed by chipping the entire contact surface to a depth of perhaps one-fourth inch or more. This process can be done in regions where mechanical equipment or high pressure water are not readily obtainable or tend to be economically unfeasible. It requires the use of chipping hammers or chisels.

3. High pressure water. A third method is to wash the contact face with high pressure water just as the concrete gains strength. The high pressure water can remove the unwanted top surface of the construction joint and expose the aggregate beneath. This process calls for careful timing and expert use of the high pressure water, but it is quick and economical. Should the timing be poor or the surface become unacceptable for other reason, then methods 1 or 2 can rectify the situation. It is the border-line

cases of washed joints that tend to become troublesome. Usually, this wash must be followed by wire brushing when concrete is fully hardened.

Mechanical bond is partly provided by roughing the contact surface through one of the three methods stated above, plus the keys illustrated in Figure 5. The spaced depressions, sometimes called "elephant tracks", may be made by inserting beveled wood members into fresh concrete, and then removing them or nailing them to the surface of the edge form for the first-placed concrete. Needless to say, these depressions become pockets for sawdust, etc., when the continuation forms are constructed, and the depressions require careful attention when the final cleaning is done. It is important that "clean outs" be provided in the forms to permit elimination of the construction debris. Therefore, these "elephant tracks" are not favored by all structural designers. (A continuous depression in the center of the wall, instead of an intermittent depression as shown in Figure 5, provides no added mechanical bond to resist forces in the plane of the shear wall.)

In order to provide better adhesion of new to old concrete, the contact surface should be treated with a cement-sand grout. Since concrete as placed in most walls tends to segregate (mortar sticks to the reinforcing steel and to the walls while the coarse aggregate goes to the bottom of the form), it is most important to place 4" to 8" of rich grout at the contact surface to provide a bed for the coarse aggregate to fill into.

It is our observation that a combination of mechanical bond, clean rough surfaces, and a cement-rich contact surface provides the best insurance for a competent construction joint.

FIGURES

Fig. 1	Construction joint movement in a shear wall in the West Anchorage High School during the 1964 Alaskan earthquake. Other structural damage was severe throughout much of this building.
Fig. 2	Detail of Figure 1. Bent bars indicate the amount of lateral movement between the upper portion of the wall and its lower portion. Note the smoothness of the construction joint which provided an excellent slippage plane. Dowel action was inadequate.
Fig. 3	Rear wall of the Cordova Building in Anchorage, Alaska after the 1964 Alaskan earthquake. The concrete was

not monolithic along the construction joint, and the aggregate had segregated when it was placed. In effect, the poor placement of the concrete had allowed the aggregate shown in this figure to act as ball bearings. The failure of the thin cement paste cover during the earthquake revealed the deficiency.

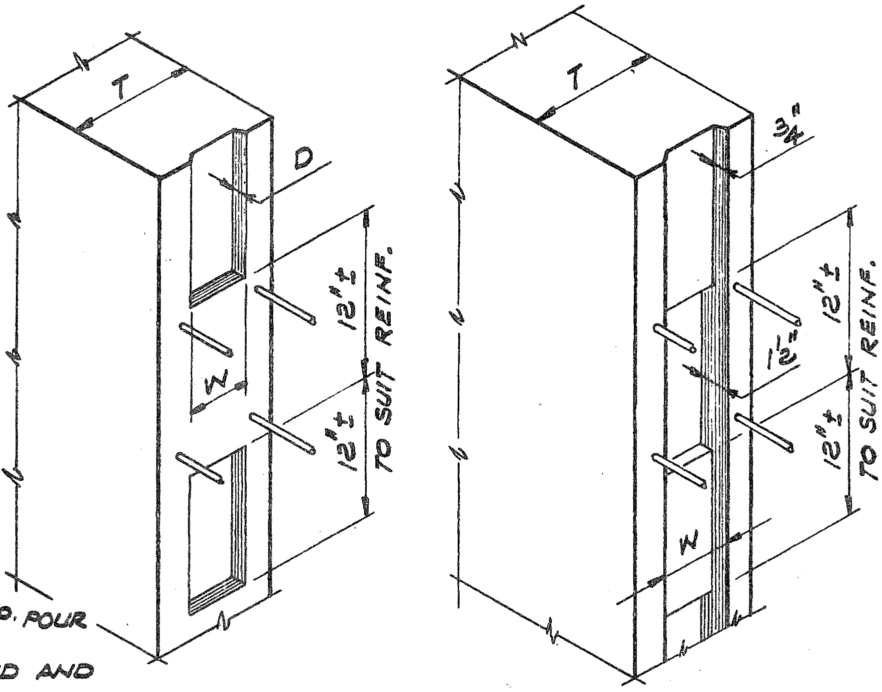
Fig. 4 South wall of the Penney Building in Anchorage, Alaska. Note slippage along the contact plane of the smooth construction joint. Temporary wood posts were added after the earthquake to prevent collapse.

Fig. 5 This is an example of a construction joint with mechanical bond provided by "elephant tracks". Details, of course, vary from consultant to consultant.

KEY SCHEDULE

T	W	D
6" SLAB OR WALL	6"	3/4"
7"	7"	3/4"
8"	3 5/8"	1 5/8"
9"	3 5/8"	1 5/8"
10"	5 5/8"	1 5/8"
11"	5 5/8"	1 5/8"
12"	5 5/8"	1 5/8"
13"	7 1/2"	1 5/8"
14" & 16"	9 1/2"	1 5/8"
27"	11 1/2"	2 5/8"

NOTE: BEFORE PLACING 2ND. POUR ALL SURFACES ARE TO BE CLEANED AND WIREBRUSHED AND MADE VERY ROUGH. REMOVE ALL LOOSE PARTICLES.



KEY TYPE #1

KEY TYPE #2

DETAILS OF POUR JOINTS IN WALLS & SLABS

DETAILS APPLY TO BOTH HORIZONTAL & VERTICAL POUR JOINTS

KEY TYPE #1 SHALL BE USED FOR ALL HORIZ. & VERT. JOINTS IN WALLS & SLABS EXCEPT BELOW GRADE.
KEY TYPE #2 SHALL BE USED FOR ALL HORIZ. & VERT. JOINTS IN ALL EXTERIOR WALLS BELOW GRADE.