BUILDING CONFIGURATION: THE ARCHITECTURE OF SEISMIC DESIGN

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INTRODUCTION

In the United States the architect's role in seismic design has been overshadowed by that of the structural engineer. The causes of this are two: US structural engineers have maintained strongly that seismic design is an engineering problem, and architects have, by default, been willing to accept this position. In consequence, seismic design tends to be delegated by the architect to his structural engineer, and US architects are not well educated in seismic design issues.

In recent years - particularly following the 1971 San Fernando earthquake - it has become clear that architectural configuration (the size and shape of the building) makes a major contribution to the success or failure of the building's seismic performance. Long recognised by engineers, this factor assumed additional importance through the use of new configurations in the 1950s, made possible by the widespread use of steel and concrete frame construction. At present this ability to construct almost any building configuration, combined with the determinants of urban building sites and planning requirements, characteristic planning solutions, and the efforts to provide interesting and unique architectural images, has resulted in a number of building typologies - building occupancy types combined with configurations - that have led to some serious problems.

While configuration alone is not likely to be the sole cause of building failure, it may be a major contributor. Historically, before the use of steel and reinforced concrete construction, good configuration was one of the major determinants of good seismic performance.

Building plans tended to be symmetrical, spans were short so that there was a high density of supporting walls, and the need for massive load bearing construction, although it increased earthquake forces in the building, tended to keep unit stresses in the materials to very low values.

With the use of modern framed structures, in which a much smaller amount of structural material is very highly stressed, irregularities of configuration will tend to result in dangerous stress concentrations and torsional forces that did not exist in more traditional configurations.

CONFIGURATION AND THE CODES

Most countries have institutionalised the solution of building problems of life and safety in the form of a code that mandates safe standards for design and construction. How do our building codes deal with the configuration and seismic design issue?

In the United States, until the 1973 edition of the Uniform Building Code, configuration was not dealt with in a specific clause at all, and at present it treats the issue only with a general caveat (1).

"Structures having irregular shapes or framing systems: The distribution of the lateral forces in structures which have highly irregular shapes, large differences in lateral resistance or stiffness between adjacent stories or other unusual structural features shall be determined considering the dynamic characteristics of the structure."

If the subject is important, why does the code treat it in only a general and suggestive way? The problem seems to be that although engineers involved in the seismic field have long recognised that configuration is a key issue, it has been found too difficult to reduce to the relatively simple set of prescriptive rules that is our typical code format. This difficulty is explained in the commentary portion of the Structural Engineers Association of California (SEAOC) Recommended Lateral Force Requirements and Commentary (1975) (2).

"Due to the infinite variation of irregularities (in configuration) that can exist, the impracticality of establishing definite parameters and rational rules for the application of this Section are readily apparent. These minimum standards have, in general, been written for uniform buildings and conditions. The subsequent application of these minimum standards to unusual buildings or conditions has, in many instances, led to an unrealistic evaluation."

SEAOC has produced updated editions of the Recommended Lateral Force Requirements and Commentary since 1959. The "Requirements" of these documents has been adopted almost verbatim into successive editions of the Uniform Building Code, but the Commentary section has not. In this section are listed over twenty specific types of "irregular structures or framing systems" as examples of designs which should involve extra analysis and dynamic consideration rather than use of the normal equivalent static force method. These are illustrated in Figure 1, which is a graphic interpretation of the SEAOC list.

Scrutiny of these conditions will show that the majority of irregularities are configuration issues within the terms of our definition. Further, our inspections have shown that somewhere between 65 and 80 percent of buildings built in the last

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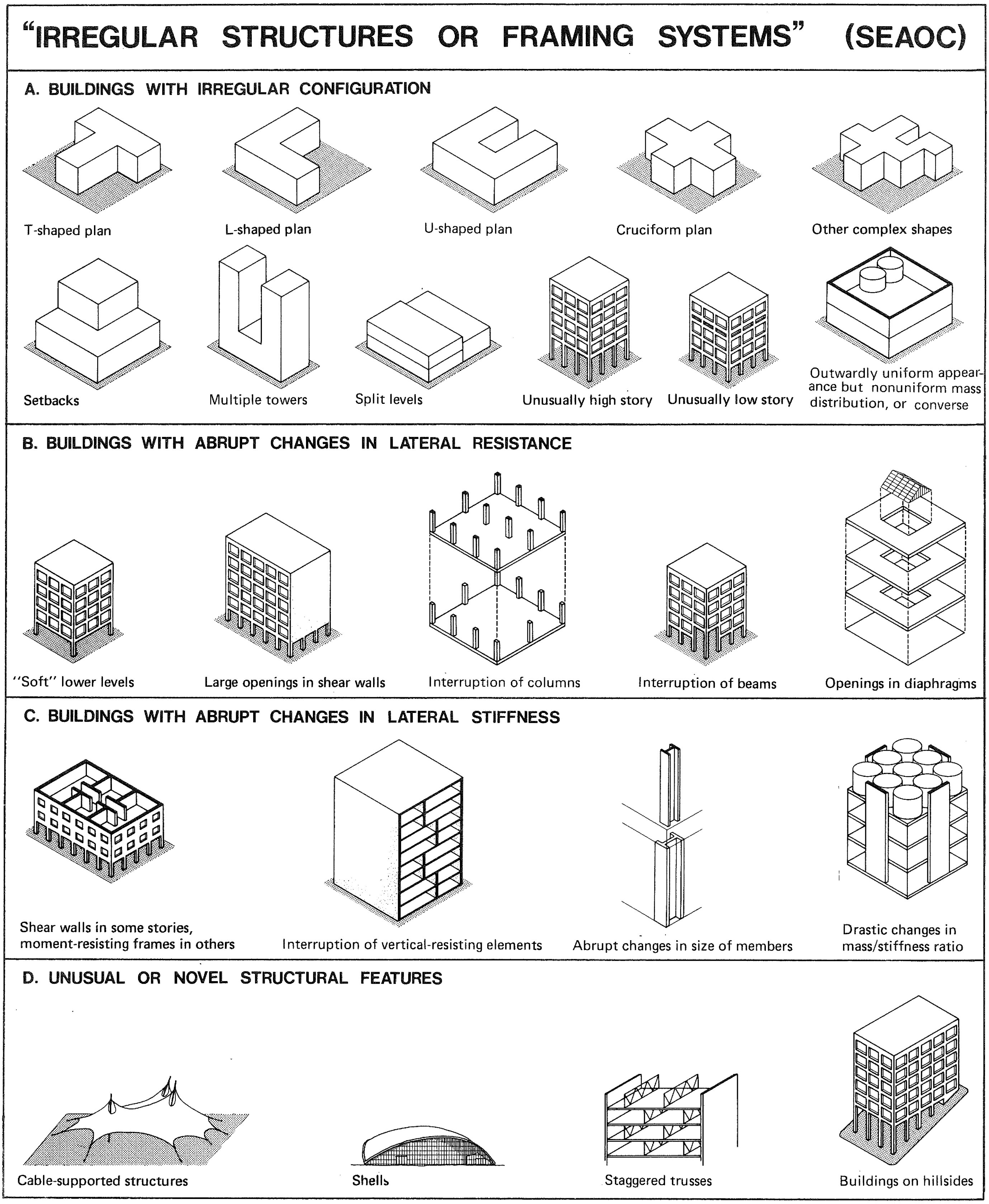

"IRREGULAR STRUCTURES OR FRAMING SYSTEMS" (SEAOC)
A. BUILDINGS WITH IRREGULAR CONFIGURATION
T-shaped plan
L-shaped plan
U-shaped plan
Cruciform plan
Other complex shapes
Setbacks
Multiple towers
Split levels
Unusually high story
Unusually low story
Outwardly uniform appearance but nonuniform mass distribution, or converse
B. BUILDINGS WITH ABRUPT CHANGES IN LATERAL RESISTANCE
"Soft" lower levels
Large openings in shear walls
Interruption of columns
Interruption of beams
Openings in diaphragms
C. BUILDINGS WITH ABRUPT CHANGES IN LATERAL STIFFNESS
Shear walls in some stories, moment-resisting frames in others
Interruption of vertical-resisting elements
Abrupt changes in size of members
Drastic changes in mass/stiffness ratio
D. UNUSUAL OR NOVEL STRUCTURAL FEATURES
Cable-supported structures
Shells
Staggered trusses
Buildings on hillsides

Figure 1.

fifteen years in the United States fall into one or more of these irregular categories: the percentage range allows for relative judgments in subjectively allocating designs to a category.

Cursory examination of the plan forms of the ten largest buildings on eight University of California campuses, a sampling which includes residential, office, library, educational and laboratory buildings, shows that 75 percent have major irregularities, and on several campuses all ten largest buildings are irregular. It is important to emphasise that these irregularities are ones created by the designers, not by problems intrinsic to the buildings themselves.

It is safe to say that well over half the buildings that have been designed recently do not conform to the simple uniform building configuration upon which the code is based and hence to a greater or lesser extent, the code forces are inapplicable. The simple equivalent static force method of the code must be augmented by engineering experience and judgment, perhaps combined with a full dynamic analysis. While major building projects will have careful engineering conception and analysis there remain many irregular buildings designed in bare adherence to the code in which, for reasons of cost or ignorance, the modification of seismic performance created by configuration irregularities may not have been carefully considered and accommodated in the design.

The above gives some indication of the difficulties experienced in the attempt to codify the influence of configuration. In work currently in progress to develop a sophisticated national code for seismic design (3) these difficulties remain essentially unresolved. It is also clear that bare adherence to the code will not ensure that the influence of configuration has been addressed.

That a situation should prevail in which the basis upon which many buildings are designed is different from that upon which the seismic code is based, is a cause not for alarm but for understanding. Conceptual recognition of problems caused by configuration predates by many decades today's analytical study. Much of the information is empirical: early observers noted the behaviour in earthquakes of buildings of certain types of materials, construction and configuration. But this situation emphasises the danger for the designer of relying exclusively on the code provisions, and not also developing a conceptual understanding of the nature of the dynamic environment and the way in which the building responds.

The configurations that cause concern are those illustrated in Figure 1. In general, the most concern is with plan irregularities that will accentuate the development of torsional forces, and with vertical irregularities that tend to produce structural discontinuities and stress concentration. In addition, variations of strength and stiffness, whether horizontal or vertical, tend to overstress the stiff elements and understress the more flexible, resulting in a structure in which a small number of elements may receive an undue proportion of the forces.

In plan, the most dangerous forms have proven to be those in which there is a wide variation of strength and stiffness between various building elevations. The performance of the Penney Department Store in the Alaska earthquake of 1964 was a notable example of the poor performance of these forms (Figure 2). In the area of vertical structural discontinuity, the problem of the 'soft first storey' and in particular a sub-class of this configuration, the discontinuous shear wall, have been revealed as the most vulnerable. The performance of Olive View Hospital in the San Fernando earthquake of 1971, and the Imperial County Services Building in Imperial County, 1979, are text book examples of the problems associated with these configurations. Both these types of vertical configuration are characteristic of modern building style and are 20th century inventions only made possible by modern steel and reinforced concrete structural technology.

OLIVE VIEW HOSPITAL, SAN FERNANDO, CALIFORNIA

The general vertical configuration of the main building was a 'soft' two-storey layer of rigid frames on which was supported a four-storey (five, counting penthouse) shear wall-plus-frame structure (Figure 3). The second floor extends out to form a large plaza: thus, in photographs, the main building appears to have a single soft storey, rather than two. The severe damage occurred in the soft storey portion, which is generally to be expected (Figure 4). The upper stories moved as a unit, and moved so much that the columns at ground level could not accommodate such a huge displacement between their bases and tops and hence failed. The largest amount by which a column was left permanently out of plumb was 2½ feet.

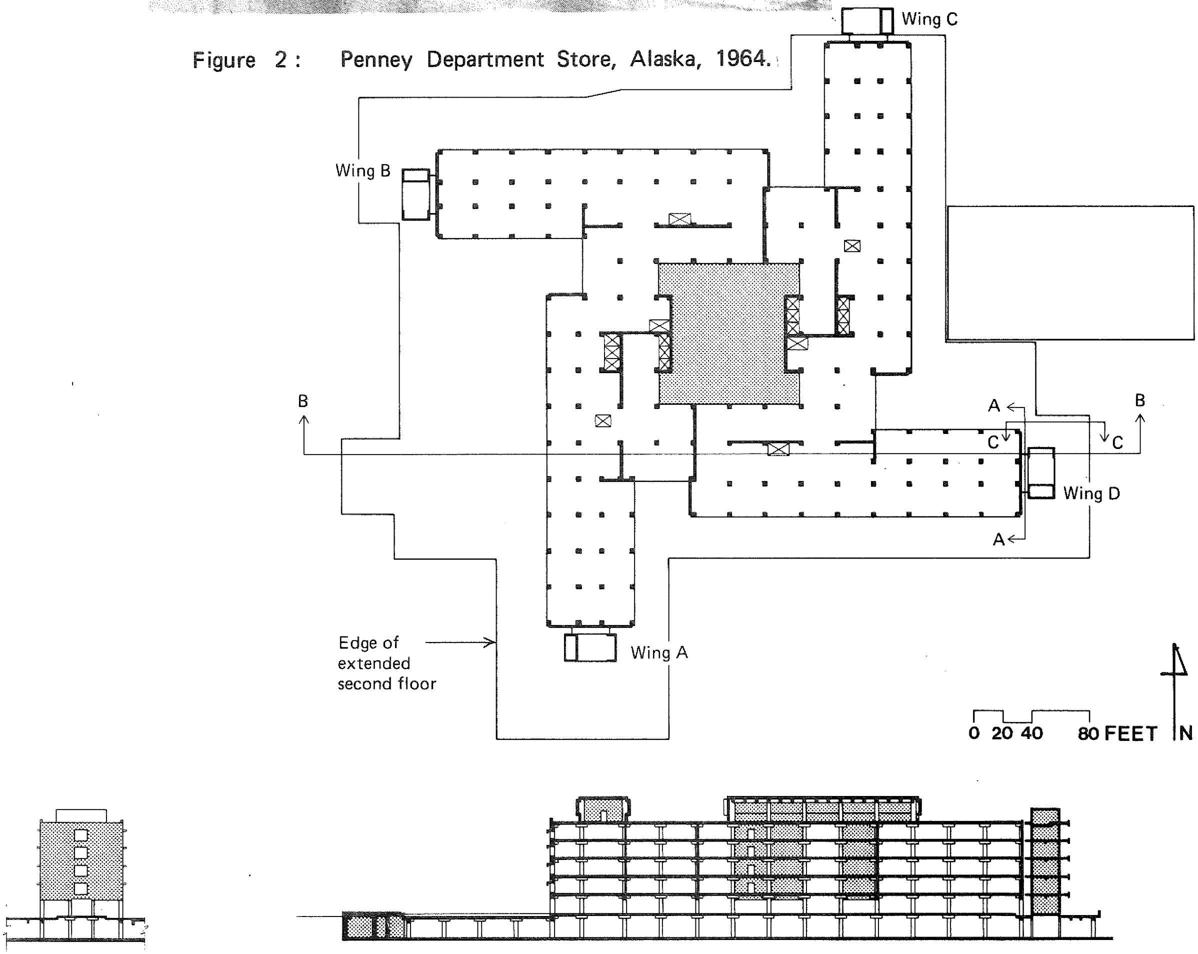
A discontinuity in vertical stiffness and strength leads to a concentration of stresses and damage, and the storey which must hold up all the rest of the stories in a building should be the last, rather than the first, component to sacrifice. Had the colums at Olive View been more strongly reinforced, their failures would have been postponed, but it is unrealistic to think that they would have escaped damage. Thus the significant problem lies in the configuration, and not totally in the column reinforcement.

THE IMPERIAL COUNTY SERVICES BUILDING, EL CENTRO, CALIFORNIA

The Imperial County Services Building, El Centro, California (Figure 5) is a prototypical example of a common building configuration of the last few decades, that of a number of repetitive floors of rectangular plan, with blank, or nearly blank, end walls that stop at the second floor level to permit an open ground floor.

The behaviour of this building in the Imperial Valley earthquake of 1979 provided a text book example of the effects of architectural characteristics on seismic

Figure 2 : Penney Department Store, Alaska, 1964.



Section A-A

Section B-B

Figure 3 : Olive View Hospital, California, 1971.

Figure 4 : Olive View Hospital.

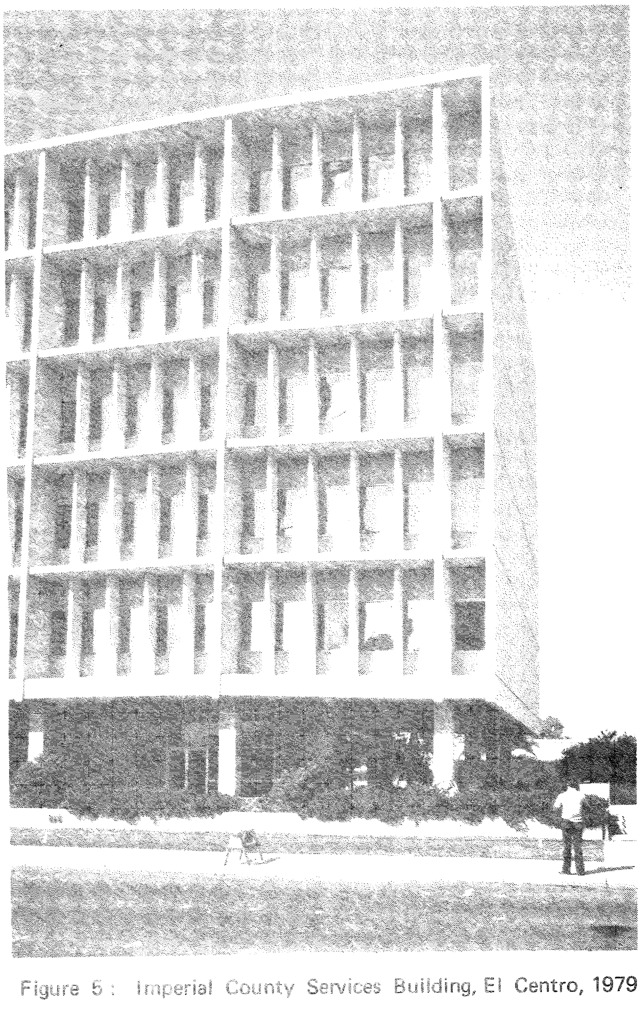


Figure 5 : Imperial County Services Building, El Centro, 1979.

resistance. The building was a six storey reinforced concrete structure built in 1969. In the relatively mild earthquake, in which only a few of the poorest unreinforced masonry buildings suffered structural damage, this building suffered a major structural failure, resulting in column fracture and shortening - by compression - at one end (the east) of the building (Figure 6). The origin of this failure lies in the discontinuous shear wall at this end of the building. The building was subsequently demolished.

The fact that the failure originated in the configuration is made clear by the architectural difference between the east and west ends (Figure 7). The difference in location of the ground floor shear walls was sufficient to create a major behavioural difference in response to rotational, or overturning, forces on the large end shear walls.

The solution to the problem of the discontinuous shear wall is unequivocally to eliminate the condition. To do this may create architectural problems of planning or circulation or of image. If this is so, then it indicates that the decision to use shear walls as resistant elements was wrong from the inception of the design. Conversely, if the decision is made to use shear walls, then their presence must be recognised from the beginning of schematic design, and their size and location early made the subject of careful architectural and engineering coordination.

CONCLUSION

Since configuration is important, and since the architect devises and controls the configuration, it follows that he is, even if ignorant, a major participant in the seismic design process. Too often the architect and engineer discuss configuration too late - when the design is already set - and in antagonistic terms. The engineer complains because the architect's configuration makes his design work difficult, expensive and even unsafe, while the architect complains because the engineer places unreasonable restrictions on the programmatic and aesthetic requirements to which the design responds.

More knowledge and understanding on both sides is clearly required. One problem in the United States is the wide separation between the two professions which begins with their education, in separate schools with very different characters and objectives. The training of the architect is primarily conceptual; that of the engineer is analytical, and the result is each profession has difficulty communicating effectively with the other.

The configuration problem is a universal concern, affects all building types, all types of construction and buildings of all ages. To the extent that the architect is influencing seismic performance through his choice of configuration, he must become better informed as to the consequences of his acts.

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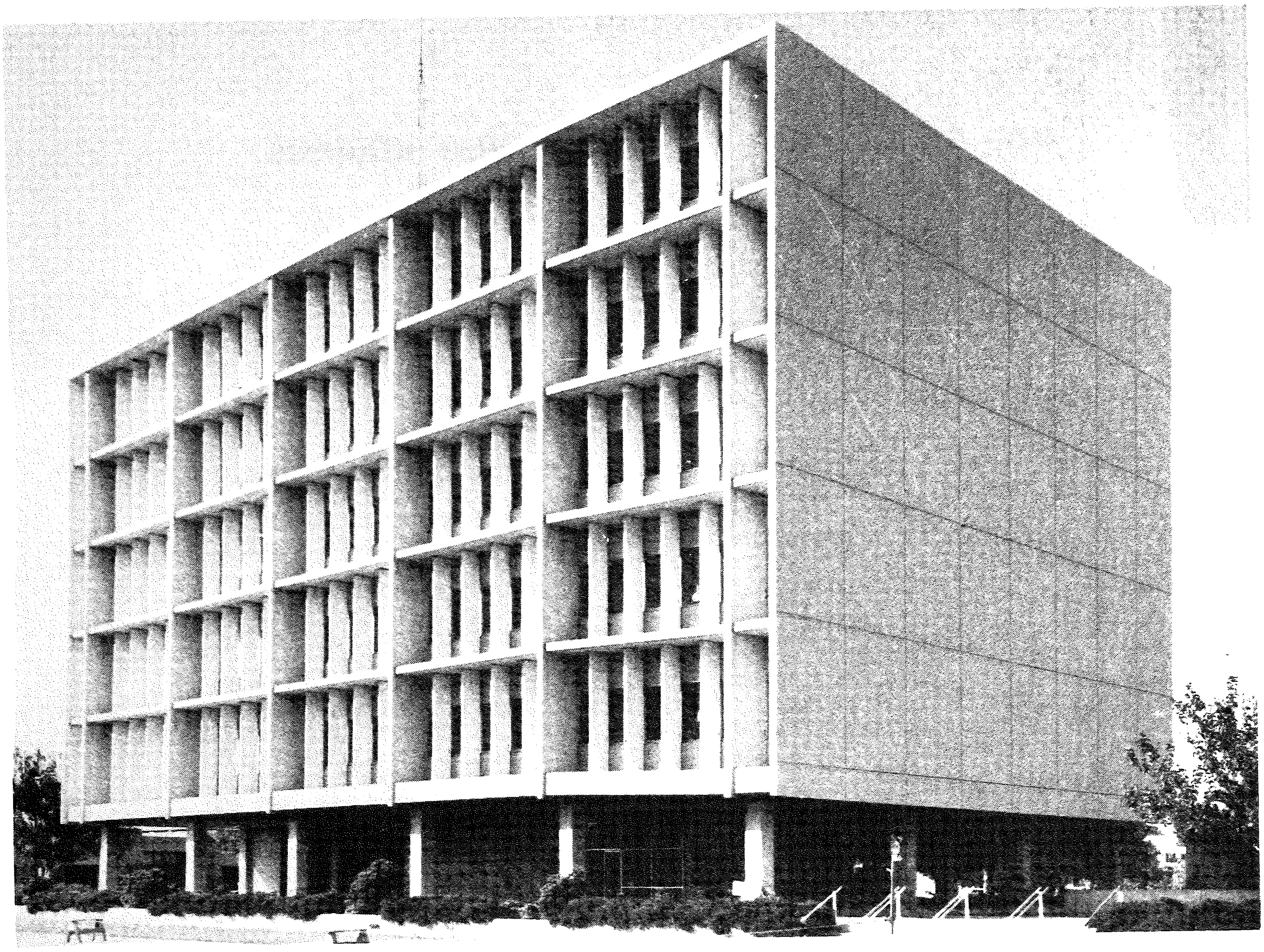
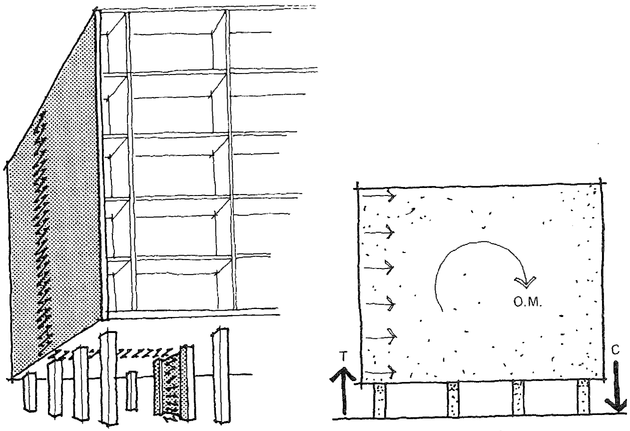
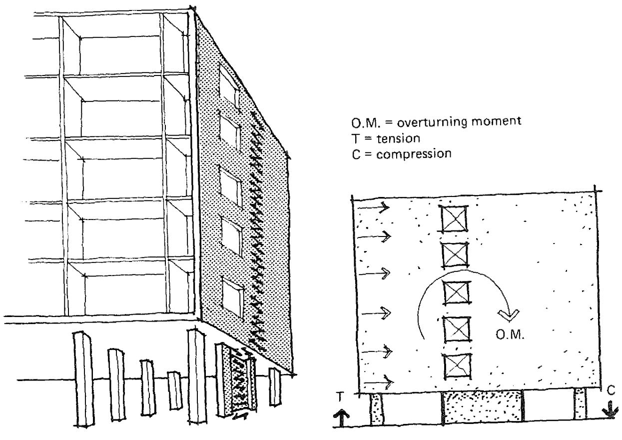




East shear wall – Translation

– Rotation



O.M. = overturning moment
T = tension
C = compression

West shear wall – Translation

– Rotation

Figure 6 and 7:
Imperial County Services Building,
El Centro.