Influence of architectural configuration on seismic response of buildings

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ABSTRACT: The influence of plan irregularities, vertical discontinuities, and building forms on the overall response of a structure to seismic excitation has not been sufficiently studied in the past, although it may have serious repercussions from the point of view of loss of life and property. This review paper presents a state-of-the-art report on the configuration issue as it relates to seismic design and emphasizes the need for further research and for collaboration of the architect and the structural engineer while deriving the building configuration for a project. A methodology of structural investigation of buildings with known configurations is proposed. A simple example is presented to illustrate some basic concepts related to configuration.

1 INTRODUCTION

Earthquake motion is so random and uncertain that it may affect a building structure in many possible ways causing damage to it. It has been long recognized by the structural engineers that architectural configuration has significant influence on building response during earthquakes. Current available research publications treat the configuration principles on a conceptual rather than an analytical basis in that very few analytical studies have been undertaken in the past utilizing a systems engineering approach. Because of the current trend in architectural circles towards the development of building plans that offer diversity in the architectural expressions and images, and the complexity of functional and conceptual aspects of a building as a natural outgrowth of the technological advances and emphasis on certain human and social issues in architectural planning, more and more buildings are being built where the architectural configuration is in direct conflict with the structural form desirable in a seismic zone. New building layout and planning concepts involving free-form massing and the adherence by many contemporary architects to the current architectural movement called post-modernism, that advocates in a way arbitrary building forms, have compounded the problem even further. Such trends must be questioned by the structural engineers not only from the idealistic point of view but also from a practical standpoint.

A synthesis of the architectural and the structural forms is highly desirable, and in the context of earthquake-resistant design wherein safety of the building is of utmost importance and concern, this becomes even more significant. This is the main theme of this paper.

2 ARCHITECTURAL CONFIGURATIONS: TYPES AND DETERMINANTS

As is well known, building configurations fall into two basic categories: (1) Plan configuration, and (2) Elevation configuration. Plan configuration refers to irregularities in the building layout horizontally that is normally drawn up by the architect. Initial avoidance of complex, long and extended shape of the building can render a building suitable for satisfactory performance under seismic loading. Some major patterns that have been identified as unsuitable on the basis of past earthquakes are L, T, U, H, and Y and other such building shapes, presence of re-entrant corners, lack of symmetry, nature and extent of perimeter resistance, core location, to name a few, some typical cases of which are shown in Figure 1. Elevation configuration refers to irregularities in the building height vertically that may cause significant problems in buildings in that the uniformity and continuity of mass, strength, and stiffness are affected when abrupt changes in these items take place. Also, a building with a high aspect ratio exhibits large lateral deflections under seismic loads. This may also cause large compressive and pullout forces on the columns, resulting in building failure. Some typical cases of problematic vertical configurations are shown in Figure 2.

The determinants of configuration are primarily a combination of activity spaces and circulation patterns as well as the geometry, geology, and climate at the location of the building. Other factors dominating the derivation of configuration are building setting, city building code requirements, and architectural requirements of style and image. It can hardly be overemphasized that violation of sound configuration principles is likely to jeopardize the structural safety when a building is subjected to a severe earthquake. It is extremely important, therefore, that there is proper and adequate interaction between the architect and the structural engineer about the matter during the initial building programming and structural planning stages. It is also necessary that the prevailing concepts of configuration based on past observations of earthquake damage are firmly implemented as well during this planning stage.

2.1 Building form selection

In determining the building form the architect usually considers the shape of the site, functional requirements, aesthetics, and client wishes which pose critical constraints to an optimum configuration. Seismic design should be considered at the start of the design process and a structural engineer with seismic expertise should be included in the design team from the beginning. Some significant considerations at the initial design stage are: structural symmetry, uniform behavior of the structural system during earthquakes, ductility and damping characteristics, reduction of seismic inertia forces by reducing the building mass, transfer of lateral forces through diaphragms, structural redundancy, connections and joints ensuring that the building components act together, etc.

3 PRESENT STATE OF KNOWLEDGE

To the best of the author's knowledge, very little research is currently being done on building configurations from the structural engineering point of view. Most of the publications to date relate to the configuration principle from an architectural perspective. Some insights into the significance of configuration in building planning were gained from various earthquakes that took place at various times. The Alaska earthquake as reported by Alexander (1964) is a good example. The Architectural Institute of Japan (1970) and the Departments of Army, Navy, and Air Force (1973) addressed the issue of configuration, while Berg (1975), Botsai (1977), Pendergrast and Fisher (1977), and Degenkolb (1977) discussed the implications of configurations from different points of view.

Dowrick (1977), Arnold (1980), Arnold and Elsesser (1980), and Arnold and Reitherman (1982), discussed the principles of configuration in considerable detail. Some other sources of information on this topic are the publications and books by: Earthquake Engineering Research Institute (1977), Green (1978), Wakabayashi (1986), and Bertero (1979). Some structural aspects of the issue of vertical configuration were discussed by Chopra (1978), and Chopra, Clough and Clough (1973). More recently, some experimental work on vertical configuration has been done by Moehle and Sozen (1980), Moehle (1980), and Moehle and Alarcon (1986). A paper on the plan irregularities and its structural implications was presented by Steinberg (1978).

As is evident from the foregoing, structural engineers have paid very little attention in the past to this subject. The configuration principles are almost always taken for granted by the engineers and the tendency is for any related development or information never to reach the practicing architect, or to reach him in a way that emphasizes design restrictions rather than developing the insight through which the architect can come up with creative and innovative solutions [see Arnold and Reitherman (1982)]. Structural engineers pursuing research in the seismic field have generally concentrated their interest on areas like methods of analysis, mathematical modeling, analytical studies, dynamical properties of buildings, shaking table tests, etc., and there are hardly any publications where the topic of configuration as a practical problem has been systematically and exclusively studied in a comprehensive manner. Although significant conclusions on configurations have been drawn in the past on the basis of investigations on damaged structures, such conclusions were, for the most part, of qualitative nature. There are admittedly some practical difficulties associated with quantitative evaluation of damaged buildings. Some main difficulties are:

1. The location of the place where an earthquake has taken place may be such that no adequate ground motion data are available.
2. Collection of data during or immediately after the shake may not be possible due to technological and geo-political constraints. Even if data are collected, they may be inaccurate and questionable. Data collected at a belated stage may not reflect the post-disaster conditions realistically and entirely. Building plans in many cases for old buildings may not be available at all.
3. Since building failures due to earthquake shocks are often of a progressive nature occurring over a very short period of time, reconstruction of events from the initiation of failure to the occurrence of major damage is a definite problem. Such reconstruction, where available from witnesses, is very helpful for the damage analysis and evaluation of the building because the results of an analysis can be quickly compared and related to the sequence of events. The progressive nature of failure in fact significantly influences the building response insofar as with each failure stage the effective configuration, and hence the stiffness of the building is likely to change.

It is interesting to note that sufficient experimental work in this area is also lacking. This is due to the fact that most of the experimental investigations that have been done before or are being done now are usually aimed at determining some basic patterns of behavior of small building models or elements. An experimental investigation on building configuration involves a multitude of cases to be covered and is obviously cost intensive. The interaction between different elements or parts of a building during a rapidly fluctuating dynamic load applied on the building model may not quite precisely simulate an actual building's dynamic properties, and hence the interaction of elements, and the complex nature of the path of seismic inertia forces through the building configuration. Despite such limitations, more experimental work in this area is highly desirable.

Although the importance of configuration as an influencing factor has been recognized and identified in the past, yet the principles have not been followed strictly. Even though these principles are known from a theoretical point of view, there have been hardly any serious efforts to validate these concepts involved for practical structures. In some cases, buildings with ill-defined or poor configurations have been found to perform well under earthquakes, and in some other cases, buildings with reasonable configurations have been found to perform badly. Past experience in this regard demonstrates that there are currently noticeable inadequacies in the realms of: (1) our basic understanding of the overall problem in its true perspective; (2) the designer's philosophy on the requirements of a building subjected to earthquakes, and (3) the scope of the currently adopted design criteria in that these code criteria do not always have a strong scientific basis. This only points to the need for more extensive research in this area.

4 SOME BASIC PROBLEMS OF CONFIGURATION

Recent developments in the field of earthquake-resistant design have demonstrated that there is a need for reviewing the design approach. Everytime there is a major earthquake, damages are observed on buildings that were thought to be designed in accordance with good design practice. Every earthquake has provided the designer an opportunity to learn new lessons. The Alaska Earthquake of 1964, the 1969 Santa Rosa and 1971 San Fernando Earthquakes in California, the 1972 Earthquake in Managua, Nicaragua, and more recently, the Mexico City Earthquake of 1985 and the San Salvador Earthquake of 1986 are cases in point. The main question to be asked in this connection is: "When can a configuration irregularity be of particular concern and how can the structural designer deal with such irregularities?" We are aware of such irregularities in general, but the nature of the overall problem is noted to be manifold. Some of the unresolved problems are:

1. How much eccentricity in plan is acceptable for a building such that the configuration is not of any special concern? Current specifications (e.g., 10 percent by the City of Los Angeles) permit arbitrary maximum eccentricities beyond which special considerations including a dynamic analysis are required. There is a disagreement on the adequacy of the 5 percent "accidental eccentricity" that is currently being added to building eccentricity. Some argue that this customary provision understates the problem.
2. How valid is the assumption of a rigid or flexible diaphragm on the basis of the relative stiffnesses of the floor and wall systems, and how can this flexibility be quantified? Since in buildings with very low aspect ratio, diaphragm flexibility plays an important role in distributing the lateral seismic forces to the resisting vertical wall or frame elements, this question needs a more positive answer than what is available at present.
3. How significant is the torsional component of the ground motion in influencing the building's response? All earthquakes have an associated rotational component which may affect buildings with low torsional stiffness. According to current estimates, the torsional moments caused by these rotations may add up to as much as 30 percent to the loads that a building must carry. Data, code provisions, and other details on this topic are very sketchy. The conventional analysis for torsion simply gives the forces on bracing elements due to moment produced by an eccentric static force. It takes no account of the torsional vibrations and the associated accelerations. Further, for dynamic analysis of buildings, response spectrum data for rotational ground motion are rarely available.
4. When can discontinuities in strength and stiffness in the vertical configuration be certainly problematic in a building and what can a structural engineer do about it? What variation of mass-stiffness ratios between adjacent stories is significant to render the building irregular.
5. Considering the interaction of the different parts and components of the building structure, what other factors may significantly contribute to the configuration problem positively or negatively?

The foregoing issues are albeit broad in scope and nature and cannot be discussed within the brief expanse of this paper. Most building codes (e.g., Uniform Building Code (1982), SEAOC (1980), Applied Technology Council (1978), etc.) presently specify some design criteria that either partially or implicitly attempt to address these questions. Obviously, there is no cut and dry answers to these questions, and usually the structural engineer considers a particular situation and responds accordingly using his best judgement. Also, there is no unique solutions to the problems. To best understand the nature of the problems and to realize plausible solutions, we have to closely observe and interpret actual damages caused by earthquakes to existing buildings and try to draw conclusions on the basis of systematic and scientific methods of analysis on damaged structures.

5 A METHODOLOGY OF STRUCTURAL INVESTIGATION

In the following, a metholodogy of structural investigation is proposed that may answer many of the questions in connection with building configuration. Such a methodology will involve the identification of damages to existing buildings with variations in plan and elevation configurations following an actual earthquake. Such identification will include the different patterns of damage and classes of buildings in terms of structural system, structural material, and failure mode, in addition to building form. The basic steps needed for such a methodology for the structural evaluation of damaged buildings may be presented as follows:

- Collect data, e.g., building plans, construction drawings, as-built drawings (where available), specifications, descriptions and photographs of damaged buildings, etc. A field survey may be required to physically assess the situation.
- Process the data collected and program a study plan accounting for the needs and objectives of the investigation project. A more clear goal of the study may be set at this stage. Classify the buildings into categories and select representative buildings for detailed study after a preliminary qualitative evaluation.

- Evaluate the selected buildings by approximate analysis, i.e., by static seismic analysis accounting for plan and/or elevation irregularities. This analysis will enable an investigator to identify the critical members and to determine the stress levels induced in the members by the earthquake. A detailed procedure may be developed in this regard to meet all relevant requirements.
- When approximate analysis does not predict structural failure reasonably, i.e., the computed lateral forces or story shears by the approximate analysis differ by a substantial margin from the actual forces and shears that would be required to induce and precipitate the failure that actually occurred to a building, or when the building configuration is complex or irregular, a detailed analysis using dynamic methods will be performed. A detailed procedure for this analysis can be developed during the course of the investigation.

Note that an agreement of the results of analysis with the actual failure will validate the assumptions. Conversely, any discrepancy in this regard will point to any fallacies or inadequacies in the assumptions concerning diaphragm flexibility, building eccentricity, etc. For example, non-structural architectural elements in a story may change its stiffness characteristics which may be ignored in the analysis. Also, the diaphragm may have been assumed to be rigid or flexible, although in reality, it may be semi-rigid or semi-flexible. On the basis of this investigation, the structural engineer can develop and recommend specific conceptual seismic design solutions for the buildings investigated using standard configuration principles. Such conceptual models derived after the investigation will certainly lead to a better understanding of configuration problems by architects, engineers, and others in the building industry.

A main effect of earthquakes on irregular buildings is, as is well known, the introduction of torsion caused by lateral seismic forces. In the following, an example is presented to illustrate this effect on a building with horizontal irregularity, and to shed some light on the architectural implications.

6 A PROBLEMATIC BUILDING

Figure 3 shows a 3-truck fire station building. Fire and police stations that are expected to stand up during emergencies following an earthquake utilize such open-front buildings frequently. Walls A — E are all 15 ft (4.57m) high and of equal thickness. The roof is made up of steel metal deck and lightweight concrete topping. Assuming a rigid diaphragm, the eccentricity on the basis of the relative wall rigidities, R, is e = 5.21 ft. (1.59m). The base shear V = 70 kips (312 kN) and the torsional moment T = 364.7 kip-ft. (495 kN.m). The total shear force on the walls are found from standard computation procedure to be:

Wall	Total Shear (kips)
A	10.80
B	10.80
C	48.41
D	2.51
E	2.51

(Note: 1 kip = 4.448 kN)

Following the alternate procedure of the SEAOC Ad Hoc Committee on ATC-3 (see Steinberg, 1978), the corresponding shears are found to be:

Wall	Total Shear (kips)
A	10.80
B	10.80
C	50.00
D	2.51
E	2.51

(Note: 1 kip = 4.448 kN)

This alternate procedure suggests that if the shear due to torsion is more than 20% of the shear due to the lateral load alone, then the torsional component is to be increased by a multiplier. This is a conservative procedure.

Assuming a flexibile diaphragm, i.e., that transmits loads in proportion to the tributary area of each element, $V_A = V_B =$ 17.5 kips (77.84 kN) and $V_C = 35$ kips (155.68 kN), i.e., a substantial increase in shear for walls A and B and a considerable decrease in shear for wall C. Since in reality, the diaphragm may neither be flexible nor rigid which values of shear should the structural engineer adopt? The diaphragm may be categorized as a semi-rigid one which is more practical to use for such a building inasmuch as a very flexible diaphragm could give insufficient support for the walls permitting the walls to fail as cantilevers. Also, a flexible diaphragm will allow the walls A and B to vibrate out-of-phase with wall C, creating major displacement problems. Conversely, a rigid diaphragm may develop considerable torsion in many instances. One may therefore utilize a semi-rigid diaphragm and may prefer to bound the problem. Generally, in most design offices, the semi-rigid diaphragm would be taken as rigid and the semi-flexible diaphragm would be taken as flexible for the purpose of evaluating the seismic effect. However, such assumptions could be erroneous. Gates (1978) studied the dynamic response of semi-rigid diaphragms and concluded that the results of simplified models (i.e., using bounds) could be non-conservative with respect to the more rigorous model.

It is noted that even a simple building like this example has many important architectural considerations. For example, the building length-to-width ratio may contribute to the building response significantly (see Degenkolb, 1977). To get the best approximation, obviously, more sophisticated analysis using detailed finite element technique in conjunction with dynamic analysis on a more realistic model is warranted. Also, a test set-up simulating a prototype like this building will be a valuable source of information on the intricate behavioral aspects. Finally, access to a 'natural laboratory' where actual structures have been damaged by a quake will be of paramount importance. Parametric studies along these lines for different variables are immediately required. It is worth noting here that the uniformity of strength, stiffness, and mass of this example building can be achieved to some extent by introducing rigid frames at the door openings. This reinforces the point that the architect and the structural engineer must discuss these possibilities and issues of materials, structural systems, member sizes, and configuration at the preliminary stage of the project. To get a better understanding of the architect's role and the need for structural-architectural collaboration, the interested reader is referred to the case studies by Homes (1976) and Reitherman (1980).

7 CONCLUDING REMARKS

The paper reviews the issue of building configuration in seismic zones. Most of the work done in the past or currently in progress relates to the architectural aspects. The principles of configuration are usually known, yet they have not been adequately verified scientifically using principles of mechanics and following a systematic methodology. Because of the importance that is currently being given to earthquake hazard mitigation, extensive research on configuration is urgently required. Such research efforts are expected to have a substantial impact on the architects and the structural design engineers. Some possible benefits of such research may be envisioned as follows:

1. Such work is expected to bring together a detailed modeling of many building configurations by utilizing a systematic engineering approach. Such a model is very desirable at present.
2. Research along this line will validate the existing concepts and provide a useful and fresh starting point for engineers and architects to collaborate on this issue.
3. It is expected to shed more light on the "configuration optimization" issue and thereby achieve more efficient structural systems while simultaneously satisfying other constraints imposed by the owner and the architect.
4. Such research may suggest if current design considerations and standards in regard to configuration need review.
5. It will lead to better building design practice and improved solutions for building renovation problems in seismic zones. It will also help improve the quality of future buildings and thereby enhance public safety.

It is the author's belief that extensive research and development in the field of architectural configuration by structural engineers will certainly strengthen the present technology base and enrich the current state of knowledge in the area of earthquake-resistant design.

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Figure 1a-1e: Reentrant Corners

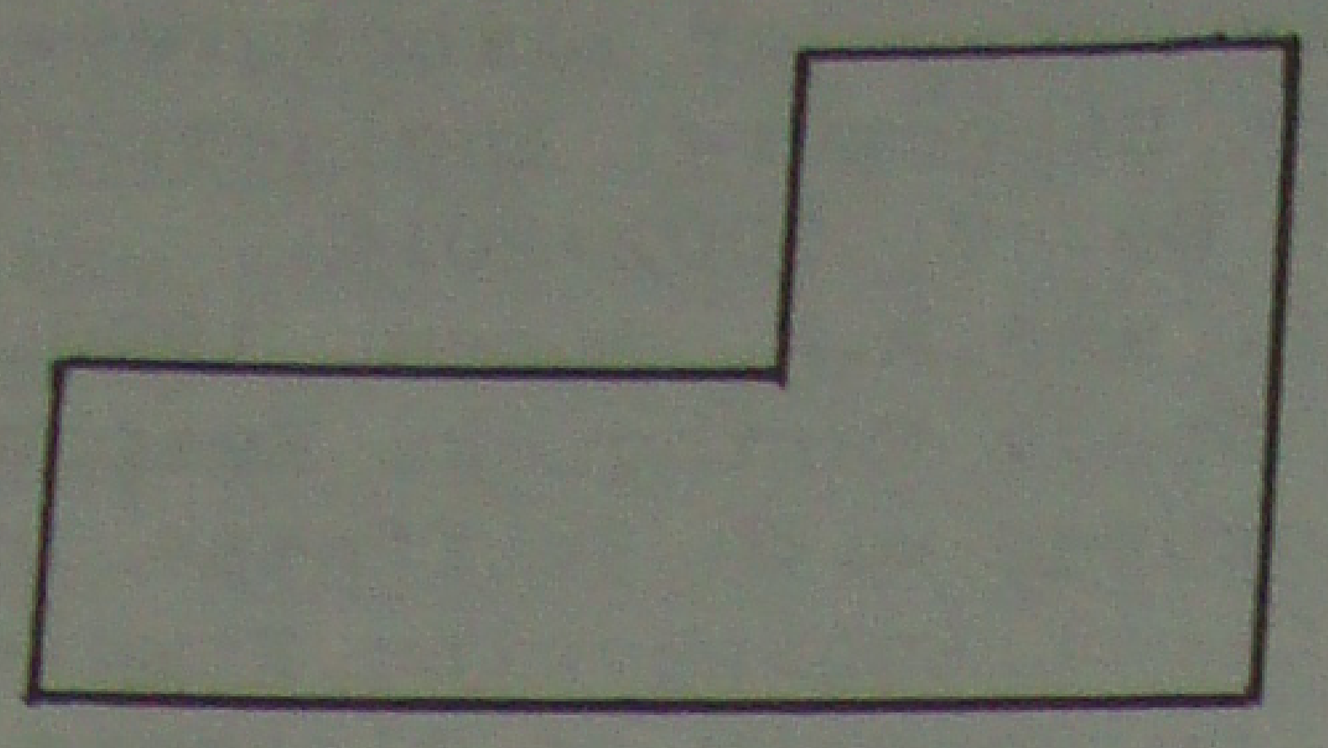


Figure 1a

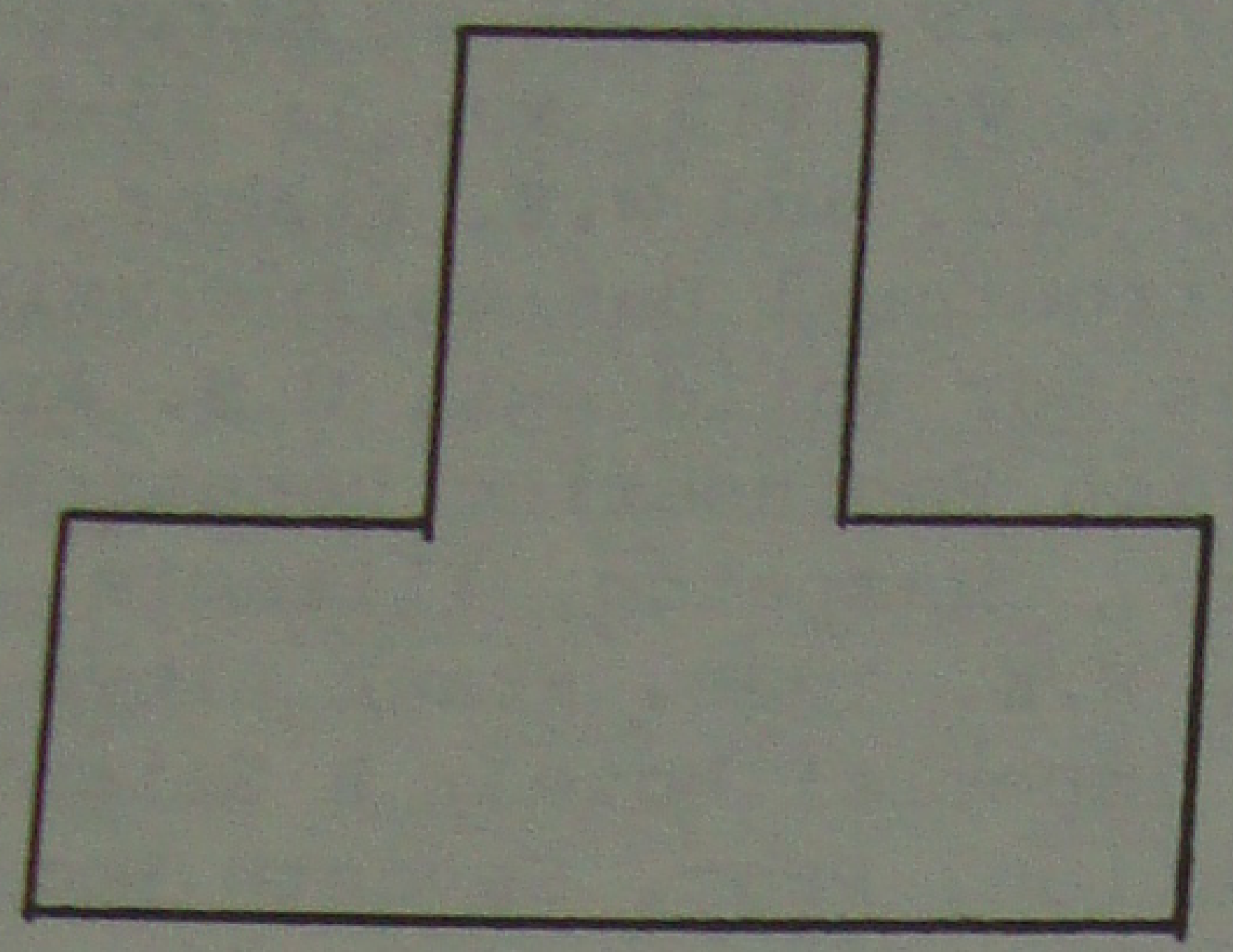
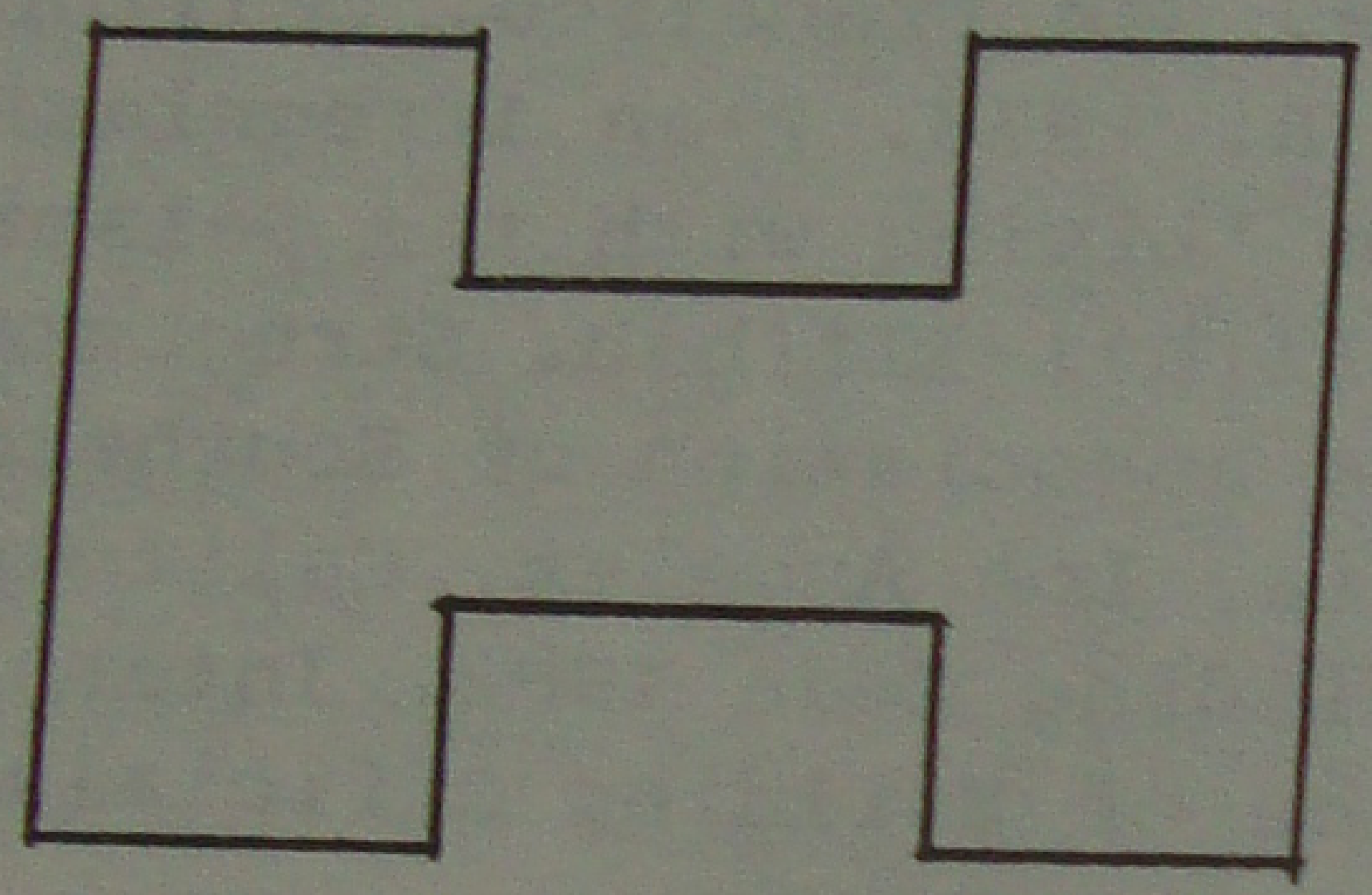


Figure 1b



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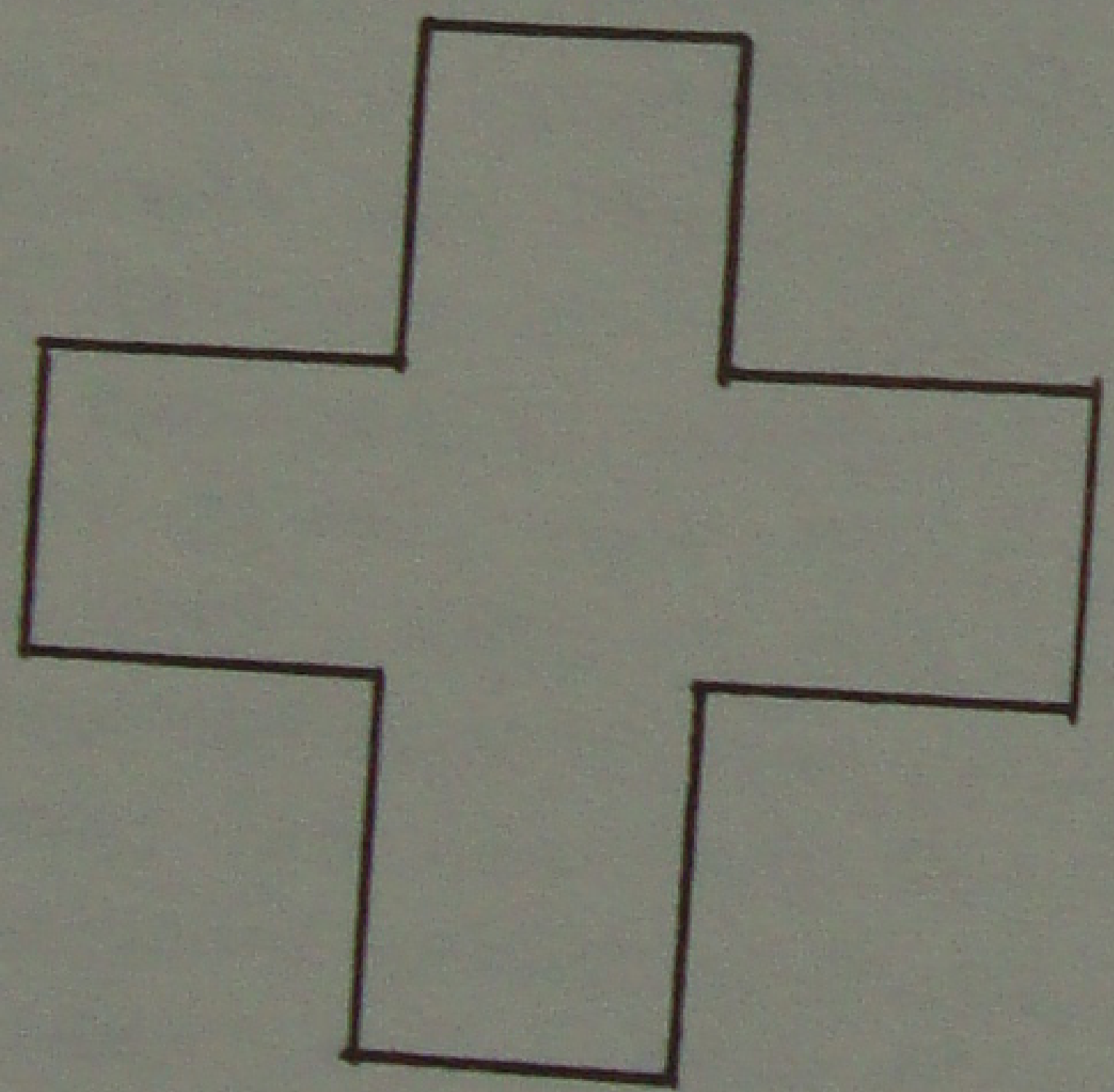


Figure 1d

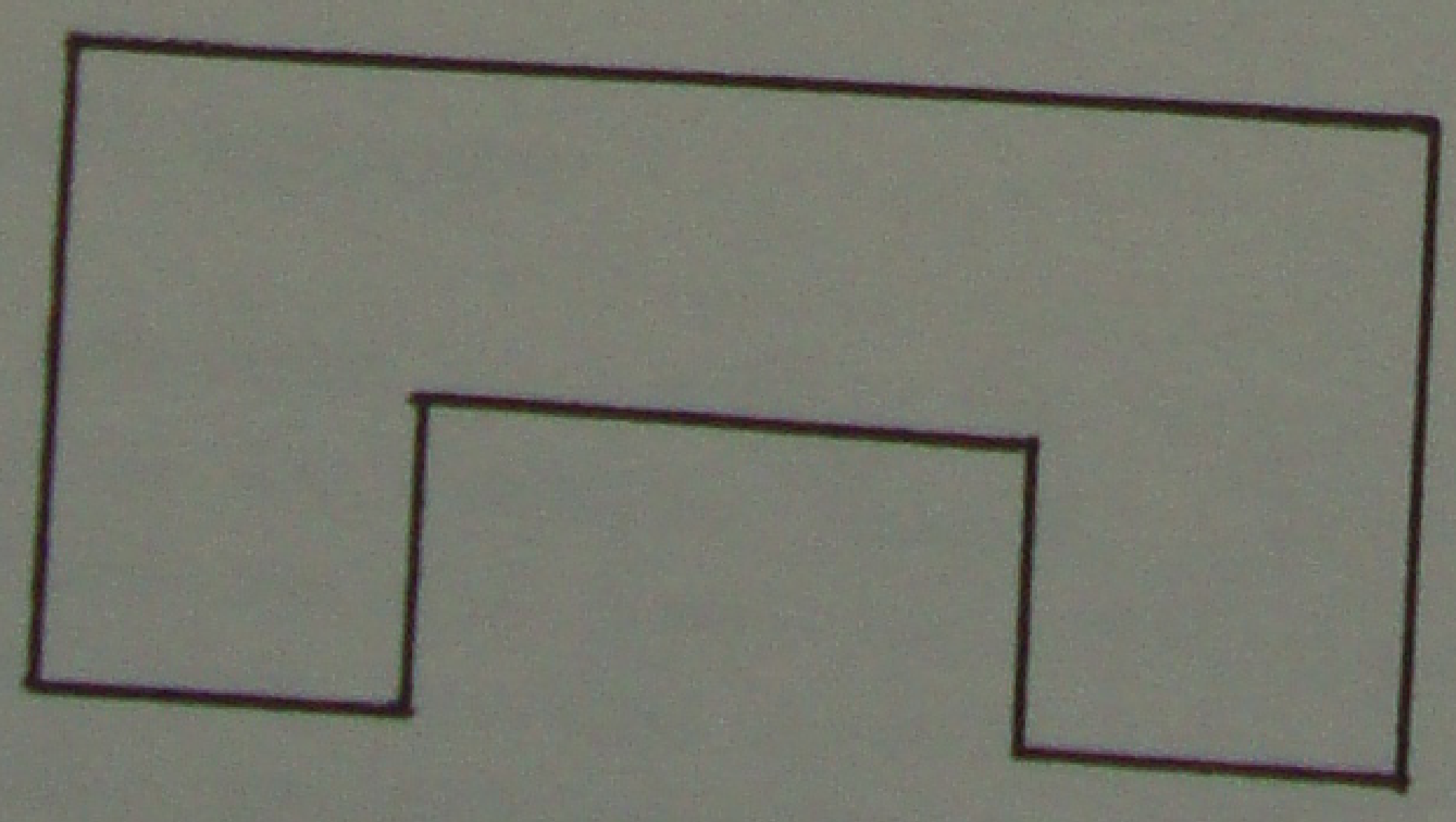
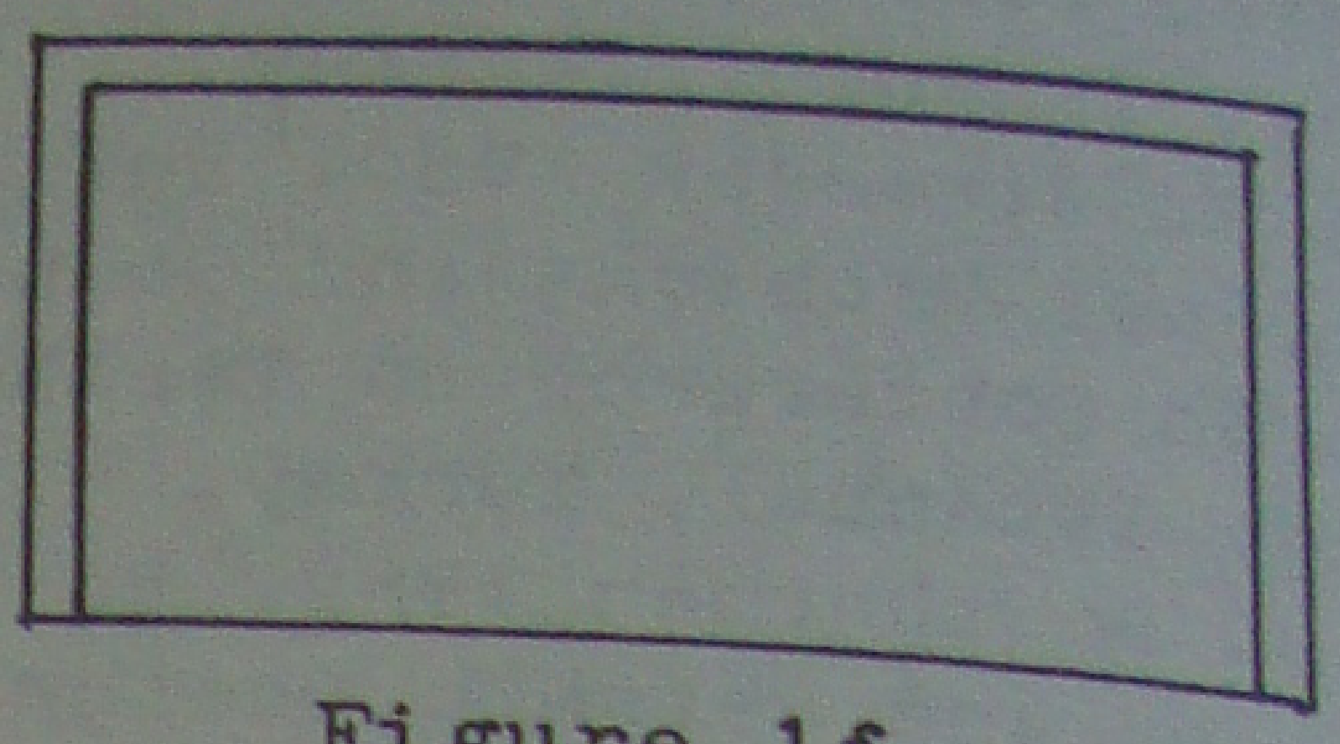


Figure 1e

Figure 1f-1h: Variation in Perimeter Resistance



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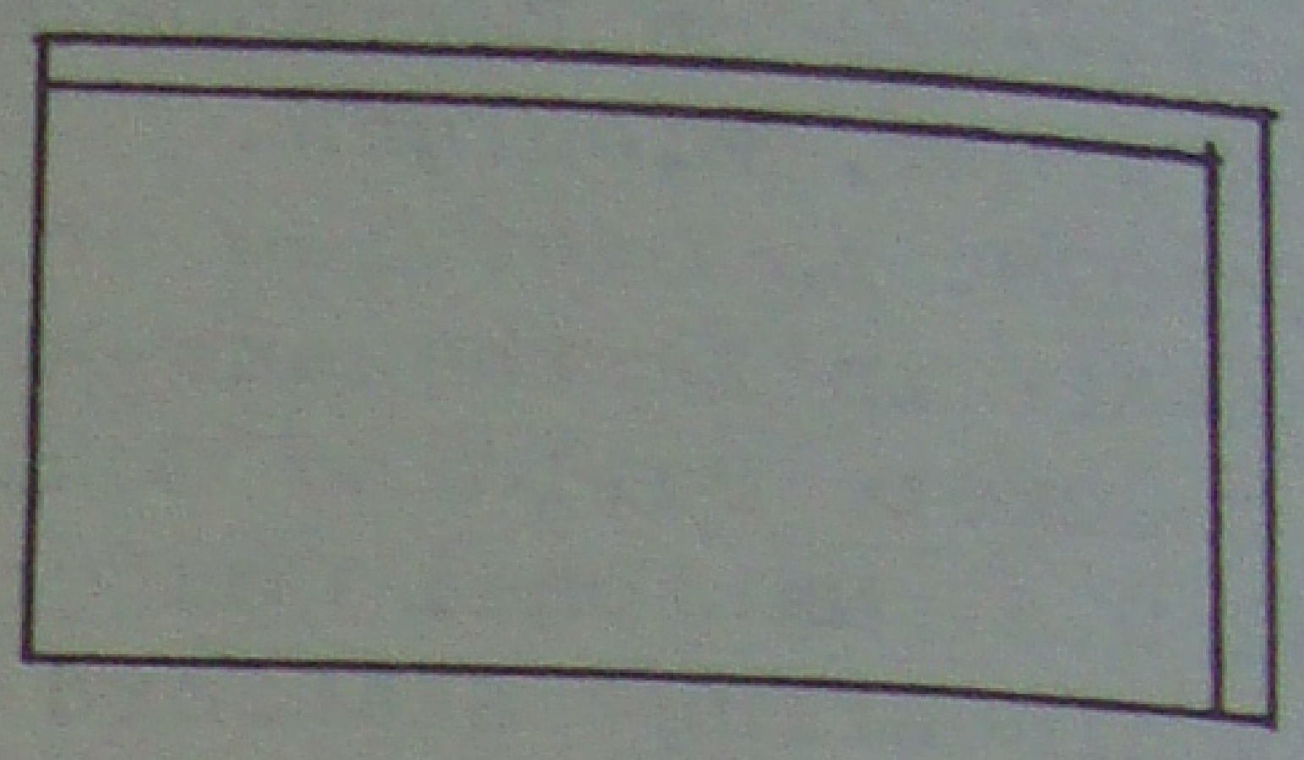


Figure 1g

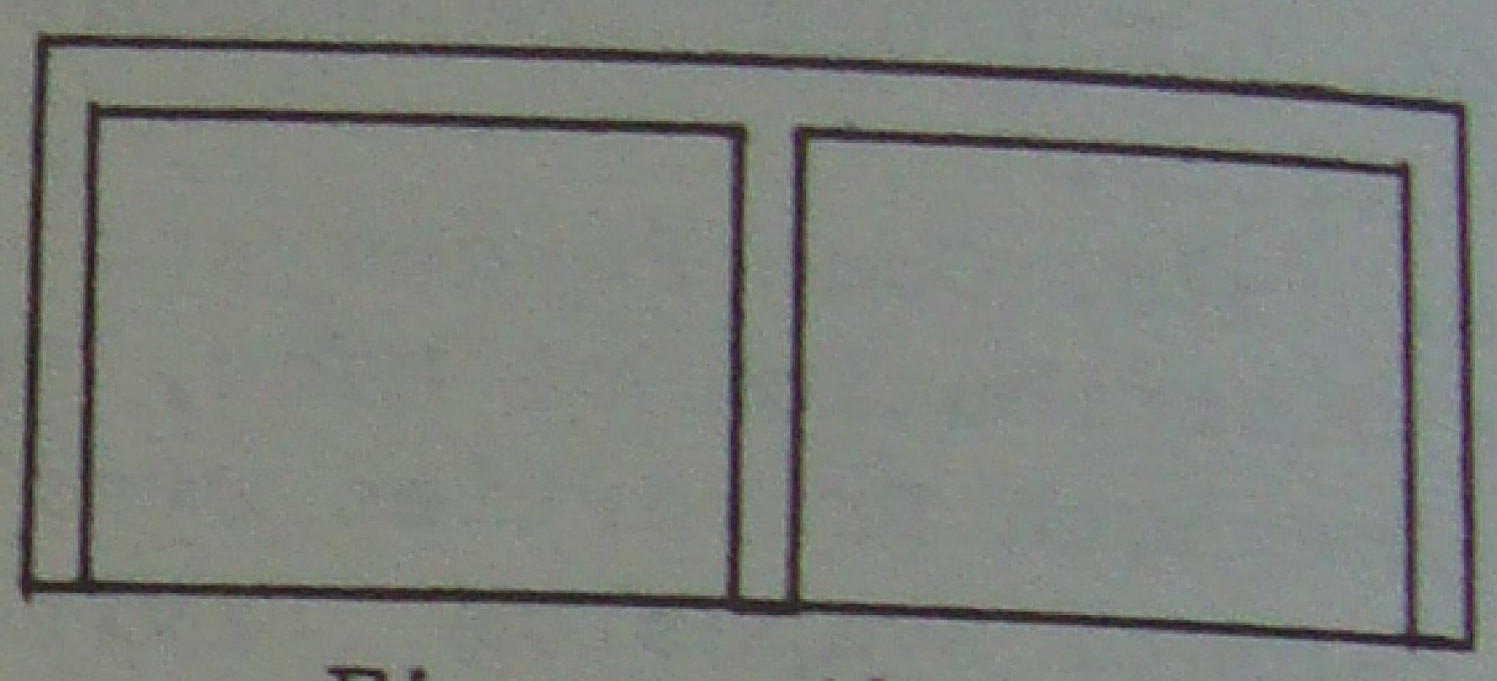


Figure 1h

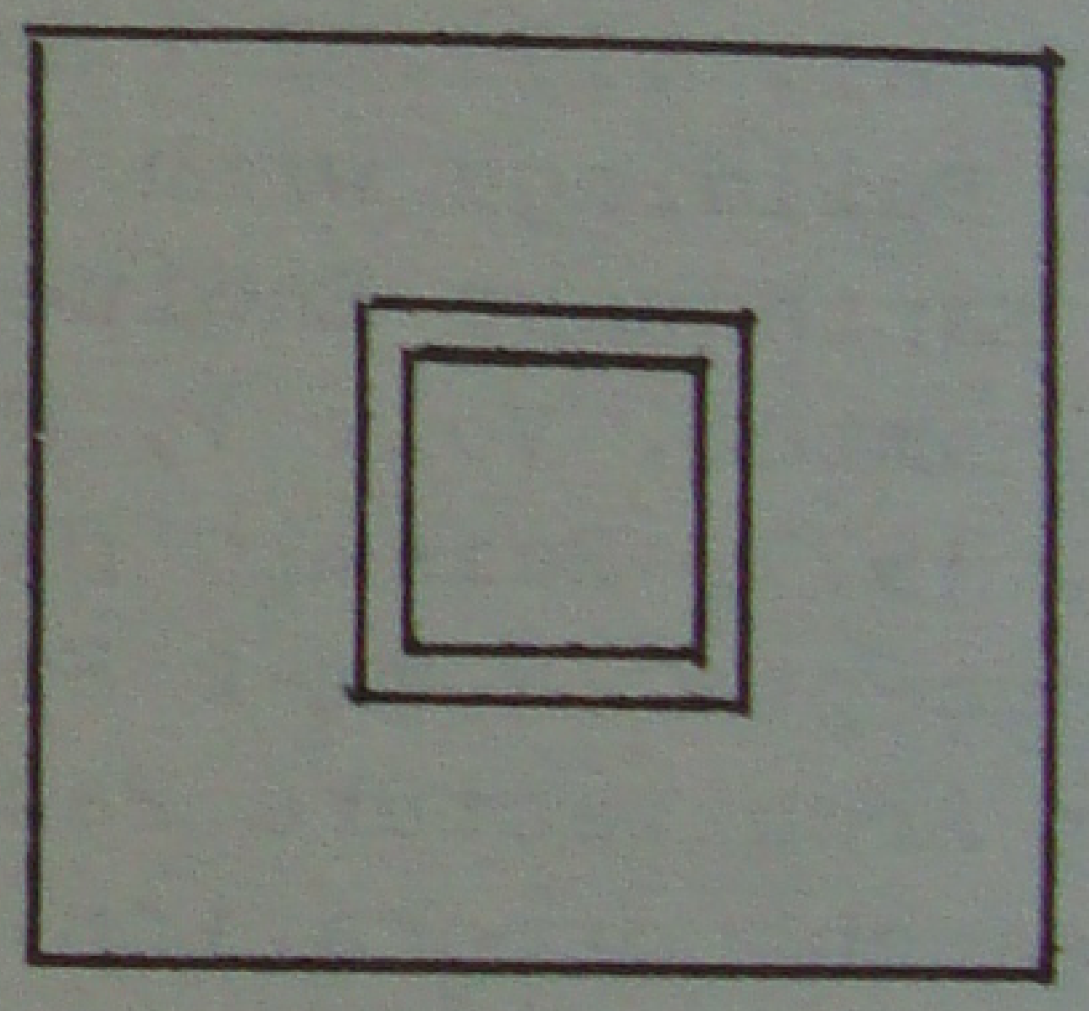


Figure 1i: Reduced Torsional Resistance

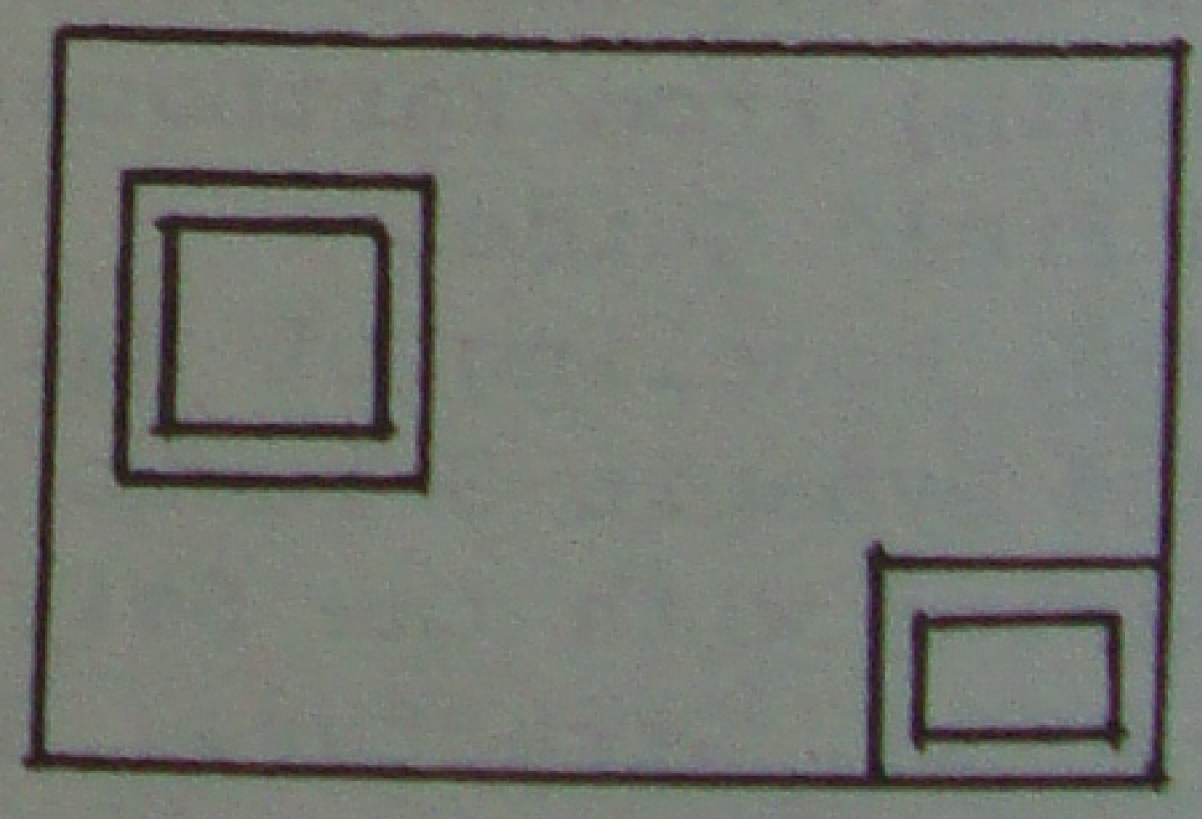


Figure 1j: Unsymmetric Stiffness

Figure 1: <u>Plan Irregularities</u>

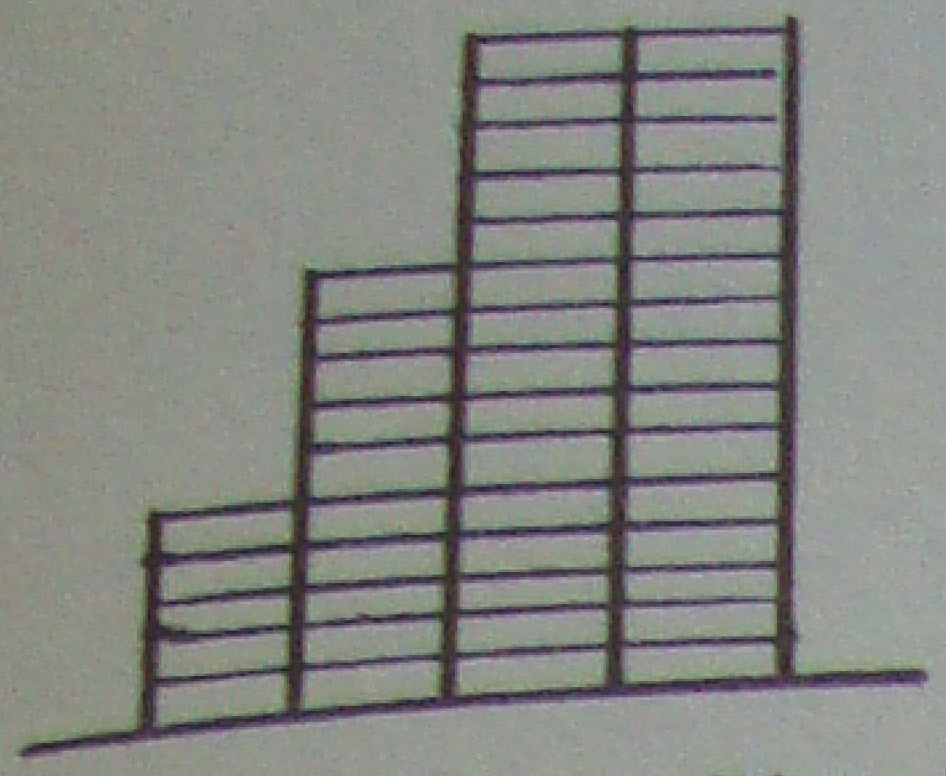


Figure 2a: Stepbacks

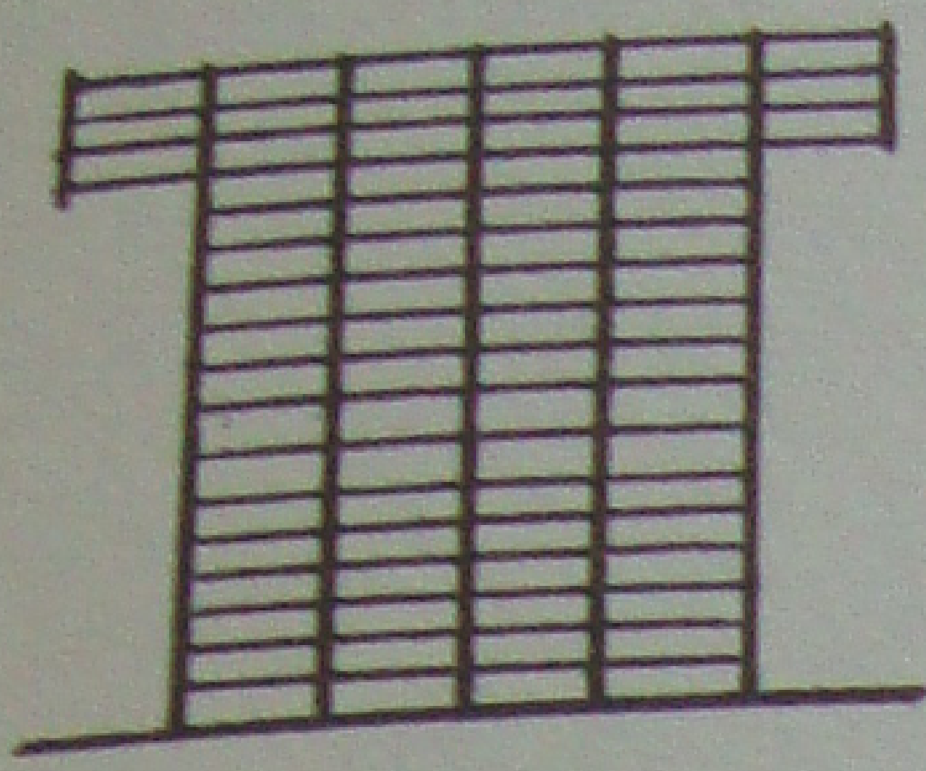


Figure 2b: Reverse Setbacks

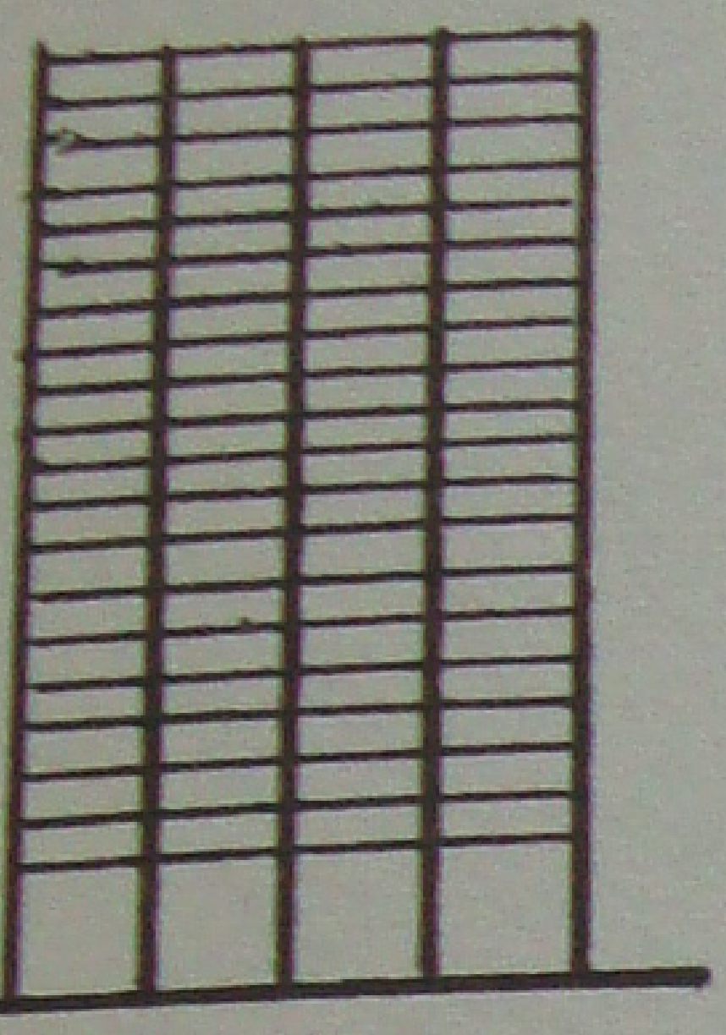


Figure 2c: 'Soft' Lower Level

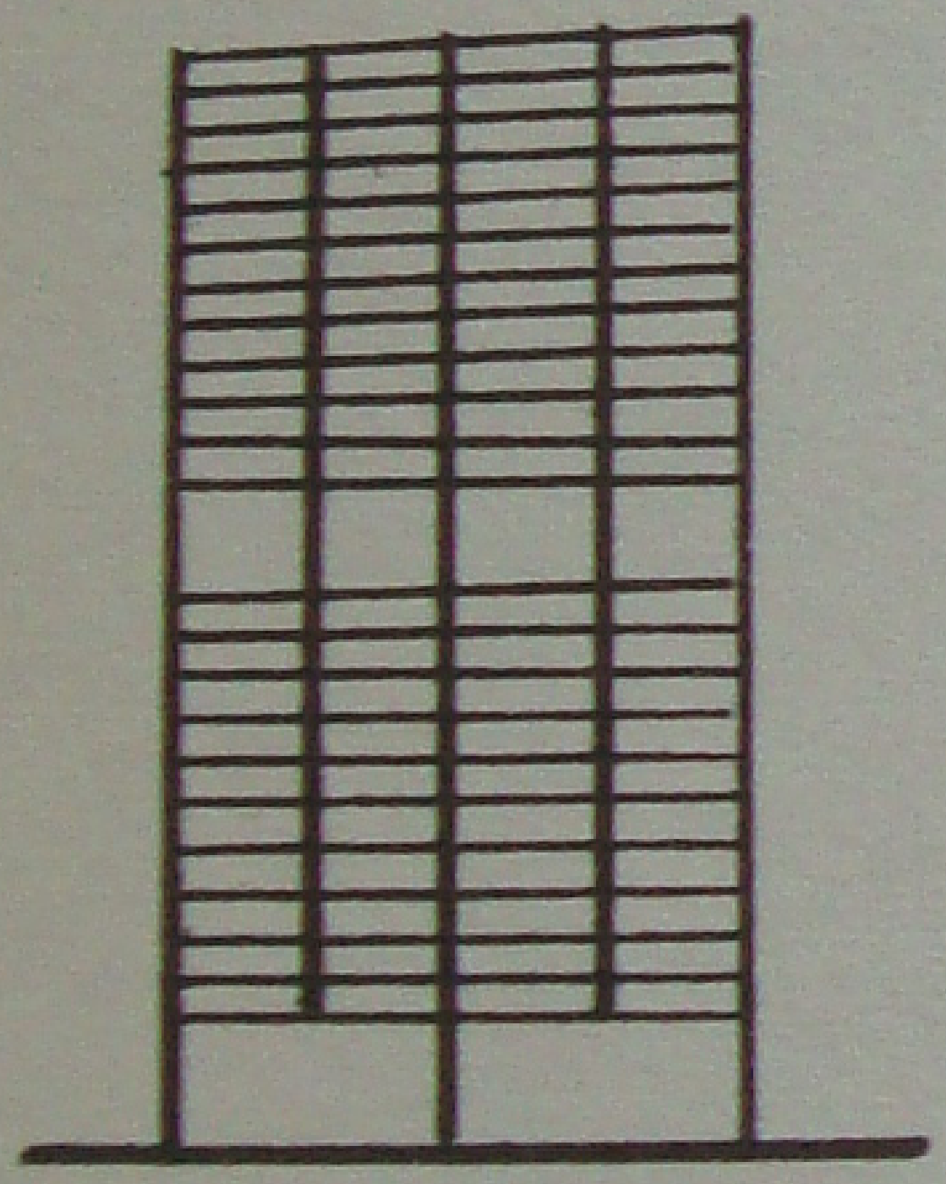


Figure 2d: Frame Story Stiffness Variations

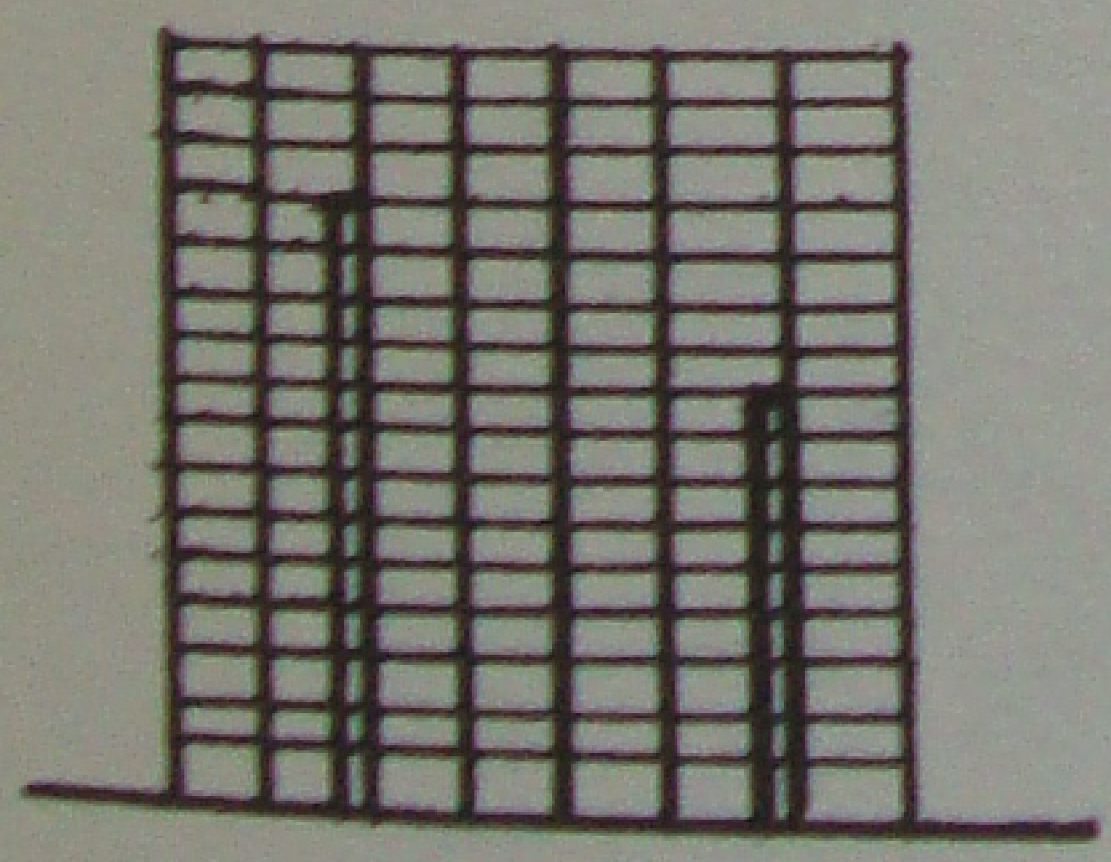


Figure 2e: Stiffness Interruption by Shear Wall Heights

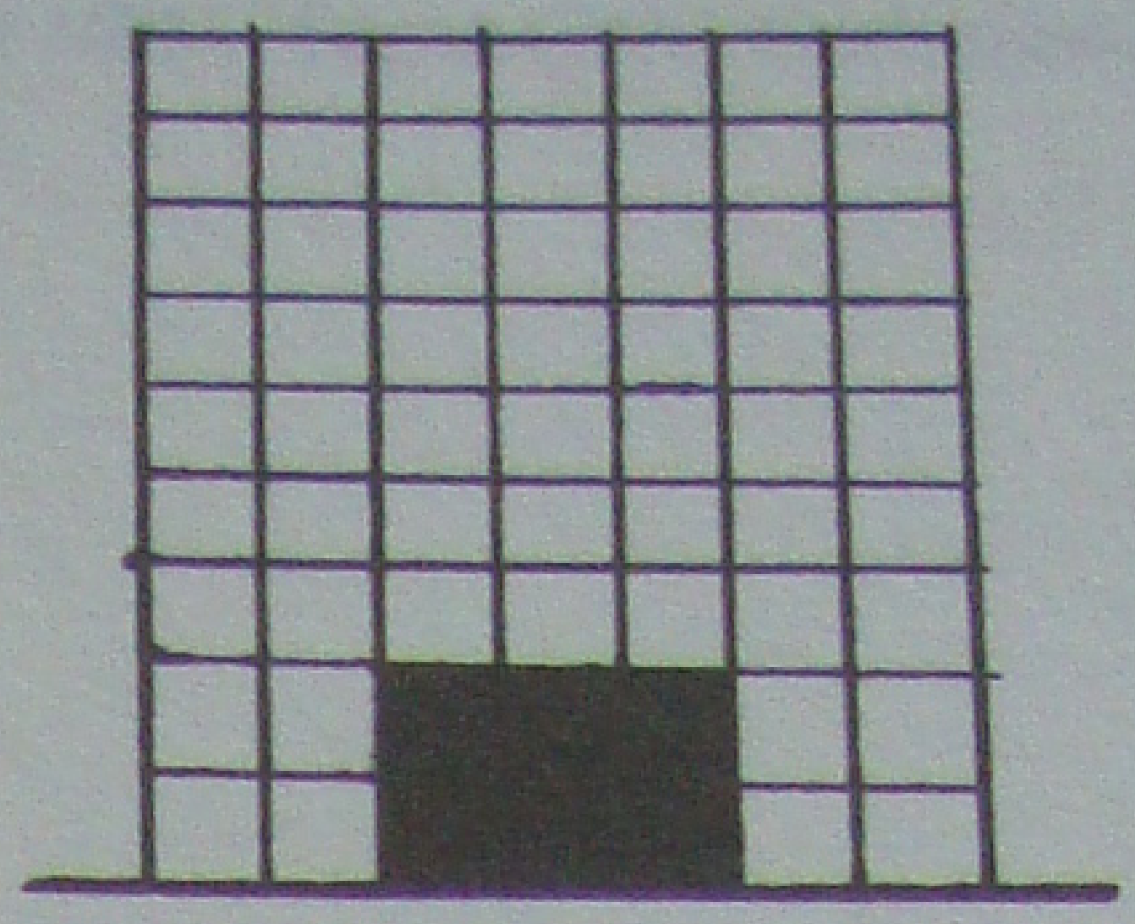


Figure 2f: Frame with Infills

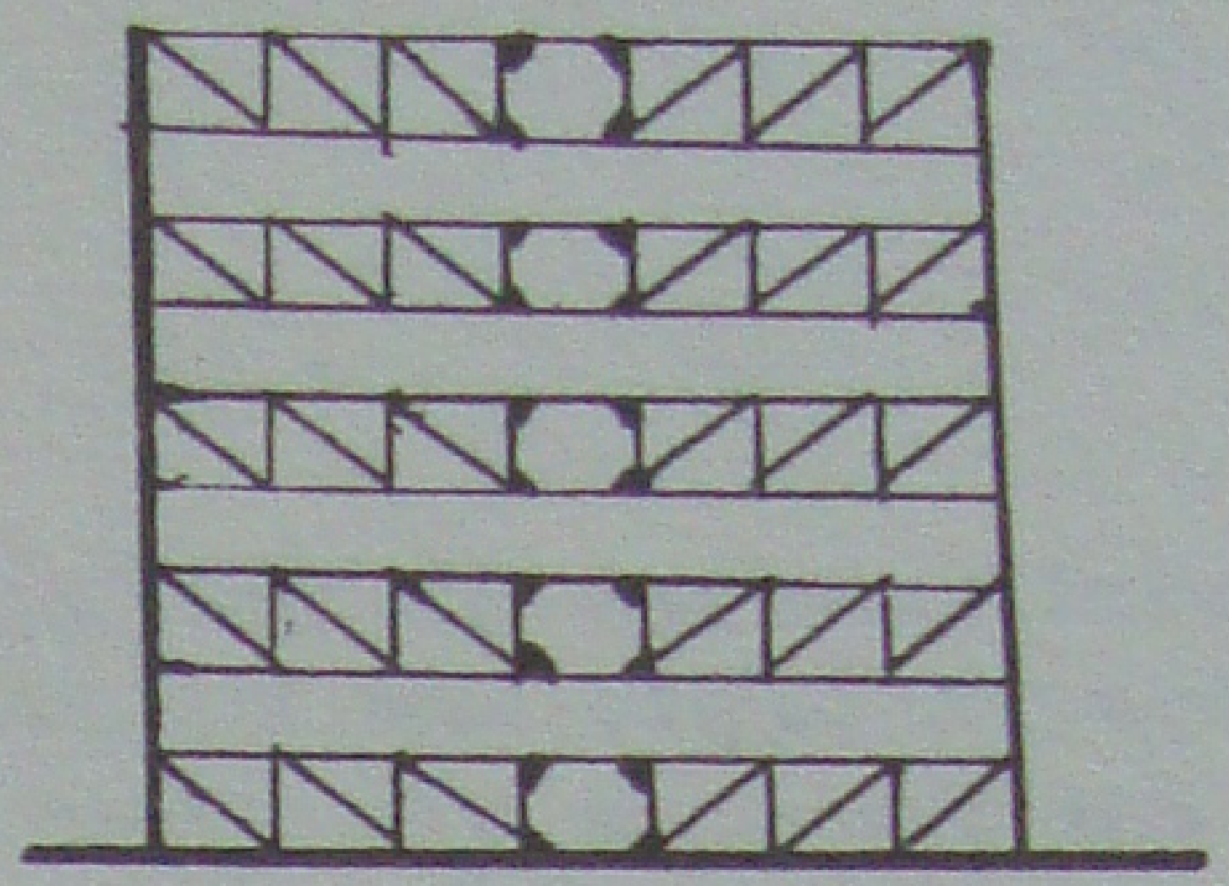
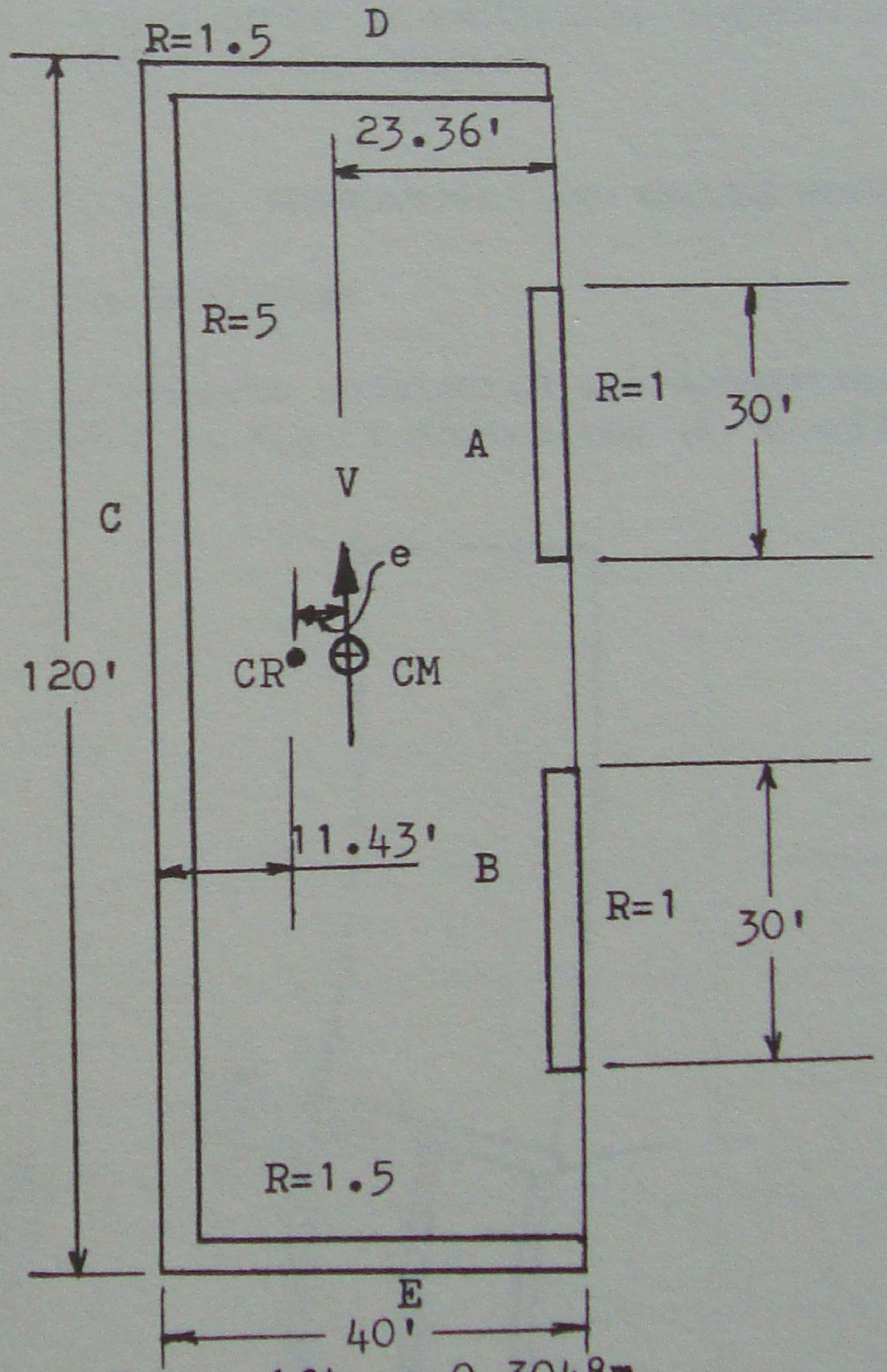


Figure 2g: Interspatial (or Staggered) Systems

Figure 2: Elevation Irregularities



Note: 1ft. = 0.3048m

Figure 3: A Fire Station Building