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The influence of earthquake forces on the selection of structural form

Influence des forces séismiques sur le choix du système et de la forme d'une structure

Der Einfluss von Erdbebenlasten auf die Wahl des Systems und der Form eines Tragwerks

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SUMMARY
In this century, structural systems for multistory buildings have been developed which can successfully resist severe earthquakes. The current empirical seismic design approach seems to assure life safety, but the attainment of the stated performance criteria for the various levels of earthquake intensity is only vaguely secured. New procedures using inelastic dynamic analysis make it possible to design structural configurations which can control the magnitude and locations of inelastic deformations and internal earthquake forces. These new procedures give the designer practical tools to modify seismic reponse to achieve economical solutions for any degree of damage control by regulating the relative strength between beams and columns.

RESUME
Au 20e siècle, des systèmes structuraux ont été appliqués avec succès à des bâtiments élévés résistants aux tremblements de terre. Les principes empiriques actuels de dimensionnement semblent protéger la vie humaine, mais les critères de performance ne sont pas remplis de façon certaine pour différentes intensités séismiques. De nouvelles méthodes d'analyse dynamique inélastique rendent possible le dimensionnement structural, et permettent de localiser les dérformations inélastiques et de déterminer l'intensité des tensions dues aux forces séismiques. Ces nouvelles méthodes permettent au projeteur de déterminer le comportement séismique de la structure pour différentes intensités; les dommages peuvent être limités par modification de la résistance relative des poutres et des colonnes. Des solutions économiques peuvent être ainsi réalisées.

ZUSAMMENFASSUNG
In diesem Jahrhundert wurden statische Systeme für Hochhäuser entwickelt, die auch sehr starken Erdbeben erfolgreich Widerstand leisten können. Die heutigen empirischen seismischen Bemessungsgrundsätze scheinen die Sicherheit von Leben zu garantieren, die Erfüllung der dargestellten Ausführungskriterien für verschiedene Erdbebenintensitäten ist jedoch nur vage gewährleistet. Neue Verfahren mit inelastischen dynamischen Analysen ermöglichen den Entwurf statischer Anordnungen, die die Kontrolle der Grösse und des Ortes inelastischer Deformationen und innerer Erdbebenkräfte erlauben. Die neuen Verfahren dienen dem Ingenieur als praktisches Werkzeug zur Anpassung des seismischen Verhaltens zwecks Erreichen wirtschaftlicher Lösungen für jeden Grad der Schadenkontrolle, indem die relative Festigkeit zwischen den Balken und Stützen angepasst wird.

INTRODUCTION

Almost a million deaths, in this century alone, have been caused by earthquakes--and most of these deaths were in damaged or collapsed buildings. Obviously, protection of life must be the primary objective of earthquake engineering of structures. The great Kanto, Japan, earthquake of 1923, in which about 70,000 people lost their lives, spurred the initiation of specific consideration of seismic resistance in the design of structures.

In the past, only certain regions of the globe were considered earthquake-prone areas, but with the development of highly sensitive seismographs, and with increasing population density in most of the world, the extent and number of such regions have been considerably enlarged.

In the initial period of consideration of seismic resistance, lateral forces were considered to be a percentage of the weight of the structure (1 to 2%); in later developments, forces similar in magnitude to those required for wind were applied. The structural solutions for earthquake resistance paralleled those developed for wind resistance, since in both cases, resistance of buildings to lateral loads were being considered.

Although random earthquake effects have components in all directions, engineering consideration has traditionally been given only to the horizontal resistance of structures. Resistance in the vertical direction has been largely neglected, since buildings have inherent capacity to resist a substantial increase in vertical loads.

It is essential to stress that there is a major difference between wind and earthquake loads. Wind loads are externally applied pressures of air moving around the building; earthquake loads, on the other hand, are inertia forces generated in the building as a response to motions of the ground upon which it rests. Despite this fundamental difference, earthquake forces have traditionally been treated as externally applied loads, since familiar procedures were available for analysis.

Stone and wood structures

Over the centuries, the determination of structural form has been defined by the construction materials used. Looking back through history at the monumental structures (not considering local, native-type housing), we find that stone was the primary construction material used in most of the world, although in certain areas many monumental structures were also constructed of wood. Stone structures used arches to bridge space, while timber structures used wooden beams to span reasonably long spaces. (Fig. 1)

The earthquake resistance of the two structural materials differs substantially. Heavy stone buildings are very rigid and have significant strength, with a substantial tolerance for overloads. The two basic mechanisms to withstand earthquakes are the shear resistance, which provides extreme rigidity, and the resistance to overturning, which utilizes the reserve compression capacity. Such structures ride back and forth with the moving ground. (Fig. 2a) The gravity load stress component of heavy stone buildings (i.e., the Egyptian pyramids, medieval castles and cathedrals) leaves a substantial margin for seismic overstress, and therefore, these short-period structures possess a relatively good degree of seismic resistance. Even many slender minarets have survived strong earthquakes.

Wood structures on the other hand, are incomparably lighter, and consequently develop substantially lower seismic inertia forces. Their flexible columns and beams bend during an earthquake and, thus, flexure is the basic mode of resistance (Fig. 2b). Also, their joints permit a degree of relative deformation between the connecting columns and beams. The flexibility of the columns and beams, with their comparatively higher strength-to-weight ratio, and the pliability of the joints, make wood a very good structural material for seismic resistance. Many larger timber structures have survived severe earthquakes.

Contemporary skeleton structures

Towards the end of the last century, with the introduction of skeleton buildings, our modern structural forms for multistory buildings began to be developed. The first such building, the 10-story Home Insurance Building in Chicago, was built in 1883 and had cast iron columns and I-beams. These initial developments of high rise structures, before the turn of the century, occurred not only in cities like Chicago, and New York (where there is no earthquake risk be considered), but also in other cities where earthquakes had long been recognized as an important factor. San Francisco had a number of these "tall" skeleton buildings clad with stone or masonry which survived the 1906 earthquake relatively well.

It must be kept in mind, however, that most of the resistance to lateral forces in these buildings was derived from the stone and masonry cladding, and from the interior masonry partitions; the skeletons in these buildings barely participated in resisting the lateral forces. In many earthquakes, the actual earthquake resistance of such heavily clad buildings proved to be substantial, and more nearly represented the old stone construction than the evolving skeletal-structural type.

In modern high rise buildings, glass and light curtain wall exterior envelopes and lightweight interior partitions, are gradually replacing the heavy masonry cladding and heavy interior partitions previously used. This evolution effected a change in the actual lateral resistance of our multistory structures--the skeleton is now becoming the primary element of lateral resistance, no longer assisted by cladding or partitions. Consequently, new design philosophies for lateral resistance are evolving.

While skeletons of the first generation of heavily clad buildings designed to a wind drift limit of 1/330 performed well under wind effects, the newer, bare-bones buildings, designed to a wind drift limit of 1/500 to 1/600, occasionally exhibit serious serviceability deficiencies, not the least of which is occupant discomfort.

Ductile Moment Resisting Space Frame

In the period between World Wars I and II, while the rigid frame was being adopted as the primary structural system for steel and concrete high rise buildings, new developments were simultaneously occurring in seismic engineering. Progress in the theory of structural dynamics shed new light on the response forces of structural systems. It became apparent that the forces developed in an elastic structure responding to a moderately intense earthquake are several times (4 to 6) higher than those specified by the codes. On the other hand, observations of the behavior of contemporary structures in earthquakes showed that, despite the relatively low design forces, these structures performed reasonably well. To reconcile the large gap between such theoretical and actual design force levels, the conclusion was drawn that structures undergo inelastic deformations during earthquake response; when the structure begins to yield (i.e., deform inelastically), no further increase of inertia forces occurs. Thus, the actual strength which is provided in the structure determines when yielding will begin and how far the structure will deform into the inelastic range by mobilizing its ductility. A structure of greater strength will delay the onset of yielding, and will utilize less ductility. Conversely, a structure designed and built with lower strength, will start yielding sooner and will deform much farther into the inelastic range, demanding a higher ductility. (Fig. 3).

Theoretical studies on single-degree-of-freedom systems indicate that a displacement ductility of 4 - 6 is needed for structures designed for code forces to resist an El Centro 1940-type earthquake. A new earthquake design approach thus resulted, in which a balance between strength and inelastic deformability (ductility) was designed into the structure. Structures composed of brittle materials (having little inherent ductility) are designed for high forces (brittle box-type structures for a system coefficient of K = 1.33), while structures composed of ductile columns and beams are designed for substantially lower forces--e.g., K = 0.67. Thus, in the 1950's the prevalent rigid frame was equipped with ductility in all its columns, beams, and their connections, and the resulting ductile moment-resisting space frame (DMRSF) became the principal earthquake resistant structural form for high rise buildings of steel and concrete. To prevent eventual instability, caused by column sidesway mechanisms resulting from hinging at column ends, and to assure the desirable beam sidesway mechanism (Fig. 4), a set of rules was incorporated into codes requiring that in a given direction the moment capacity of columns be larger than that of the beams at a joint. The intention was that hinging should occur in the beams and not in the columns.

An important advantage perceived from using the flexible moment resisting space frame was the longer period of vibration, as compared with that of a more rigid structure, which results in lower earthquake forces.

Flexibility - ductility

It is important to draw a distinction between the terms flexibility, as opposed to rigidity, and ductility, as opposed to brittleness. (Fig. 5) These terms are sometimes mistakenly interchanged. Beyond the limit of its elastic deformations, a flexible element or structure can be either brittle (susceptible to crushing or disintegration) or ductile (pliable). On the other hand, a ductile structure can be either rigid or flexible, depending on the amount of lateral deflection caused by a unit of lateral force. Inelastic deformations can occur only in ductile elements or structures.

Once inelastic deformability (ductility) became identified as the main structural characteristic needed to resist earthquakes, it followed that the strength of all the members of the structure should be governed by flexure, and that no premature brittle shear failures should interfere with the process of yielding at critical nodes of the structure. Ductile yielding in critical nodes redistributes the moments to the lesser stressed locations of the structure until all hinges needed to create a collapse mechanism are developed.

A set of details to assure ductility of columns and beams and their connections was introduced into earthquake codes (Figs. 6 and 7). At the same time, the use of brittle elements such as shear walls for the primary elements of seismic resistance of concrete buildings was discouraged by specifying higher seismic forces for them. In a similar way, braced frames (vertical trusses) were discouraged, to avoid compressive buckling failures of steel truss members.

It should be noted that for earthquake resistance of inelastic buildings, deformations are as important as stresses, since beyond the elastic limit of member capacities, plastic deformations continue to increase with stresses remaining at yield level. Therefore, any approach considering only elastic stresses cannot deal realistically with either safety or damage control.

Choice of structural material

The two basic materials for highrise structures are steel and concrete, while wood continues to be used effectively for lowrise buildings. Due to its inherent ductility as a material, structural steel is often perceived to be superior for seismic resistance. Experimental studies during the 70s demonstrated that reinforced concrete beams, columns and shear walls can be specially detailed to have ductility in a range similar to that of structural steel members. On the other hand, some steel sections may buckle before reaching their yield capacity, thus having no ductility at all.

Seismic resistance of a structure depends not so much upon the structural material used as upon the structural form selected, and the details used. It also depends upon the appropriateness of the structural form for the given material. For example, steel is more efficiently used for linear members (columns and beams), whereas concrete is more effective in plate action such as in slabs and shear walls. It is possible to design good and bad structures with either of the two materials.

Nonstructural elements

During the last quarter of a century, while the concept of the ductile moment resisting space frame has been predominant for earthquake resistance, there has been an ongoing transition in the construction industry in the use of "nonstructural" materials. The older, heavier cladding materials such as stone and solid masonry are gradually being replaced in building elevations with glass and light curtain walls; masonry partitions are being replaced with lightweight partitions made of gypsum, wood or plastic. In some countries outside the United States, hollow clay tiles are replacing solid masonry in exterior walls and in interior partitions. Some of the newer partition materials are rigid and brittle (hollow clay tiles), while others create resilient partition assemblies. Most of the newer materials have low strength, consequently, their contribution to the lateral resistance of the frame may be minimal.

Observations in earthquakes, and inelastic dynamic studies, indicate that modern buildings may have interstory distortions in the range of 1 to 1-1/2 in. in response to severe earthquakes.

When flexible, resilient, interior partitions and exterior cladding panels are used with flexible frames, the seismic distortions of the frame can be followed by the nonstructural elements without damage. However, when brittle infill is incorporated into flexible frames, the seismic distortions of the frame can cause damage to the brittle partitions, occasionally with an explosive release of energy and damage to the frame. Therefore, brittle elements should not be built into flexible skeletons, unless details are provided to allow frame distortion without straining and damaging the rigid, brittle nonstructural elements. (Fig. 8)

Experience in earthquakes

Ever since the San Francisco earthquake of 1906, evidence is available that a great number of contemporary buildings in various areas of the earth have been subjected to and have withstood severe earthquakes. As construction and design procedures have improved, records show that an increasing percentage of multistory buildings have performed satisfactorily, amply demonstrating that it is possible to build structures which will withstand earthquakes of major intensity. While brittle-type structures, such as those of unreinforced masonry, usually have performed poorly in major 'quakes (as might have been expected), structures designed with some consideration for earthquake forces have demonstrated a full spectrum of behavior ranging from poor through merely adequate to excellent. In numerous cases (e.g., in Central America, Romania) where recent codes were implemented, the performance of some structures has been very good, confirming the general validity of the direction of our codes for regular well proportioned buildings without drastic stiffness changes from level to level.

On the other hand, if we look at the examples of failure of contemporary concrete and steel buildings in the various 'quakes, we can see that most of the failed structures were not designed for earthquake resistance. Of the failures of buildings designed in accordance with recent codes many were directly attributable to drastic changes in stiffness between successive stories. The extreme changes caused large distortions of the more flexible stories, with subsequent collapse due to brittleness of columns.

Following each of the recent earthquakes, modifications in either the design forces or reinforcement details, or both, were implemented into codes, thus generally advancing the state-of-the-art.

It should be noted that a significant number of the buildings observed in earthquakes contained "nonstructural" elements which were not considered in the analysis, but which substantially contributed to their seismic resistance. Therefore, caution must be exercised in drawing conclusions concerning the adequacy of structural systems based solely on the observation of performance of such buildings.

Experience in earthquakes shows that while details are extremely important, the role of structural form in determining seismic response cannot be overemphasized. No amount of excellent details can improve the poor performance of an ill-conceived structural system. Sources of major distress during earthquakes have been structural layout deficiencies such as: substantial asymmetry of members resisting the lateral forces; large differences in plan dimensions between the two orthogonal directions; large discontinuities in stiffness and strength between subsequent levels, and others.

Shear walls and braced frames as elements for lateral resistance

Concrete load bearing walls (unreinforced and reinforced) have been incorporated into buildings for as long as concrete has been used. In the 1950s modern shear walls, acting as cantilevers, were introduced to stiffen frame-type buildings. Owing to the high rigidity of walls, as compared to the frame, the entire lateral resistance was assigned to the walls, and the columns, slabs and beams were designed for gravity loads only. While this approach may appear safe, since all the loads and their effects seem to be accounted for, the frame is actually underdesigned, because its deflection-induced moments, shears, and axial forces have not been considered.

In the 1960s, practical analytical methods were developed to consider the interaction between frames and shear walls. The major beneficial effect of the interaction is a set of internal forces (tension and compression, shown in Fig. 9) between the frame and the walls which drastically reduces the overall deflection, thus increasing the stiffness of the interactive system. Such added stiffness, without added cost, permits the construction of very tall buildings economically, mostly without paying a premium for height. This means that such buildings are designed for gravity loads, and the effects of wind are accommodated within the 33% increase in allowable gravity load stresses.

These advanced analytical methods have resulted in new shear wall-frame configurations which could not have been devised previously due to a lack of analytical tools. New structural types have dramatically improved the efficiency of wind-resisting structures.

While new rational approaches have been utilized to develop alternative structural systems for wind resistance, the continued use of elastic analysis (which inadequately represents inelastic response) has inhibited the development of more effective and efficient structural configurations for seismic resistance.

Observation of seismic performance of shear walls

Beginning with the Kanto (Japan) earthquake of 1923, the earthquake records of recent times indicate that buildings containing shear walls perform considerably better than frame-type buildings, both with respect to safety against collapse as well as control of damage to nonstructural elements. The presence of shear walls, even when substantially cracked during an earthquake, prevents collapse by hindering formation of column sidesway mechanisms. The presence of the shear walls also limits the interstory distortions, thus lessening damage to nonstructural elements.

On the contrary, frame structures are much more flexible, and respond with substantial interstory distortions during an earthquake, leading to damage of brittle nonstructural elements, finishes and contents of the building as shown in Fig. 10 from the 1967 Caracas, Venezuela earthquake.

While in earthquake after earthquake examples can be cited in which shear wall structures have demonstrated superior behavior, as compared with frame structures, codes still discourage the use of shear walls by specifying higher load factors for them and lower permissible strength. It was only during the early '70s that questions were raised regarding the preferential status of the ductile moment resisting space frame versus shear walls.

While in the early 1980s there is already widespread recognition of the need for shear walls to improve seismic resistance of concrete structures, the discussion continues among professionals on the choice of flexible vs. rigid structures. To avoid resonance, it is necessary to stay away from a certain period of vibration, when the period of the soil is definitely known. However, except for Mexico City, there are very few locations in which the period is known with certainty--too few to warrant making an exact period the major structural criterion. In addition, period determination is not yet an accurate exercise; a taller, rigid structure may have the same period as a flexible structure with half the number of stories. The many advantageous aspects of more rigid shear wall and truss-type buildings such as: superior damage control due to smaller interstory drift, simplified ductility details, simplicity of detailing of nonstructural elements, etc. by far outweigh the possible lower inertia response forces generated in flexible structures.

Development of new structural forms -- shear walls

In the '70s, extensive experimental programs on shear walls were carried out at a number of universities; these studies produced a large body of information showing that shear walls can be made ductile by special proportioning and detailing of reinforcement. Walls with a balance betweeen flexural and shear strength, with an upper limit on shear stresses, and with proper reinforcement distribution and detailing can provide the ductility level that may be required in major earthquakes. It may not be desirable to rely on ductility of shear walls as the primary energy-dissipating mechanism of a structure; however, available ductility in walls makes them a most obvious element to interact with frames for lateral bracing and to provide a second line of defense for energy dissipation.

Slitted shear walls

Another method for utilizing ductility in shear walls was recently developed by Japanese engineers. The slitted wall concept (Fig. 11) was introduced to make possible the incorporation of shear wall panels into steel frame multistory buildings. Slitting the walls converts a story-high panel into a number of flexible vertical elements, achieving two objectives: (a) the brittle shear-governed behavior of the story-high shear panel is transformed into flexure-governed behavior of the individual vertical slender elements; and (b) the high stiffness of the wall panel is reduced so that the deformation of the slitted wall becomes close to that of the frame. As a result, the two elements can cooperate effectively in resisting lateral loads.

Shear wall-frame interactive systems

The state-of-the-art in seismic design for highrise buildings is still dominated by the moment-resisting space frame. Highly efficient structural systems for wind resistance, developed on a rational basis, are only slowly and cautiously being introduced in high risk seismic regions. For the low and moderate risk seismic regions, new work is in progress to provide earthquake resistance by using the efficient shear wall-frame interactive structural systems designed for wind as a point of departure. The strength and detailing of the beams is then modified so that they will respond inelastically and dissipate energy. The walls and columns are designed to remain elastic for the design earthquake, and to utilize a limited amount of their inelasticity only in the event of a hypothetical maximum credible earthquake. Such desired response can only be achieved by using inelastic analysis techniques.

Inelastic response history

Recent improvements in computer technology (both hardware and software) have brought inelastic dynamic response history analysis within the reach of practical design. Response history analysis is a step-by-step tracing of the response of a structure to an earthquake accelerogram in small time increments. The use of such analysis makes it possible to consider the yielding of individual members and to incorporate into the structure the necessary ductility details only where required, thus eliminating the costly ductility details in places where they cannot be utilized. The new approach leads to a more rational design resulting in controlled seismic behavior. It also provides the engineer with a new, powerful, tool with which he can devise innovative, more effective structural configurations to dissipate seismic energy--systems we were not able to devise before because of a lack of means to analyze them. It is hoped that the inelastic procedure will advance earthquake resistant structural design technology just as the shear wall-frame interactive methodology advanced wind resistant structural design in the 1960s.

Serviceability and stiffness

The major structural difference between wind and earthquake-resisting structures is that for wind, the members resist factored loads within their elastic range, below the yield level, while for earthquakes, the members are designed to deform beyond the yield level, into the inelastic range.

Inelastic deformations of structural members cause their permanent distortions. Although such distortions of beams may create unsightly cracking, it is the accumulation and spread of inelastic deformations in columns which may eventually endanger the structural stability. To ensure life safety, therefore, inelastic deformations in columns must be kept within tolerable limits.

Serviceability as related to tall, wind-resisting structures, is determined by interstory drift which affects nonstructural elements, and by wind vibrations which affect comfort of occupants.

In the evolution of modern structural systems for tall, wind-resisting structures, stiffness of the overall system has been the primary criterion for acceptance, measured by interstory drift. The maximum allowable drift, in turn, depends on the ability of nonstructural elements to distort without distress and without losing their ability to function as needed. This, of course, is in addition to stability considerations.

In seismic structures, comfort of occupants during an earthquake becomes of secondary importance, while interstory drift and its effect on nonstructural elements becomes the prime serviceability consideration.

It has been established that the magnitude of overall deformations in a structure are about the same, whether it resists an earthquake elastically or inelastically. Since earthquake damage to nonstructural elements in a structure is largely determined by the interstory distortions, the control of such damage requires that a sufficient amount of initial elastic stiffness be designed into the structure. Depending on the intensity of the "design" earthquake, the minimum rigidity needed for acceptable control of seismic damage to nonstructural elements may exceed that required to control wind drift.

The relationships between stiffness and strength of a structure, and its ductility demand, are complex. More rigid structures generate higher seismic inertia forces and consequently, require a higher design strength which affects ductility demands. In general the major influence on ductility demand results from the actual strength level for which a structure has been designed.

The selection of the structural system for seismic resistance can be made in two stages:

1. Stiffness is selected to result in a wind drift within the elastic range, to satisfy the wind serviceability requirements (drift and vibration);

2. Then, the strength level determined for wind resistance is gradually modified to result in an elastic plus inelastic (ductile) seismic drift within a limit to assure damage control.

It follows that a desirable overall approach to finding an economical and efficient seismic structure is to start with the most efficient structural configuration based on stiffness to satisfy wind requirements, and then progressively modify the strength of its members under earthquake forces until a desirable balance between strength and ductility is achieved.

CONCLUSION:

Looking towards the next stage of earthquake engineering development, it seems that our ability to protect life should be taken for granted, and the task of protecting property through damage control should now receive our full attention. Flexible frames, detailed for ductility, are well suited to provide earthquake resistance in structures (such as bridges, stadiums, some types of industrial buildings, etc.) where large earthquake distortions do not damage nonstructural elements and do not affect their subsequent functional performance. However, in residential and commercial buildings, in which the structure represents only 20-25% of the building's cost, controlling damage through control of earthquake deformations becomes an important design consideration. For such buildings, structural systems containing shear walls and trusses are gradually gaining acceptance in seismic regions. For wider utilization of shear walls and trusses, designed on a rational basis for damage control and for controlled inelastic seismic action, new simple inelastic analysis methods (static or dynamic) now need to be developed.

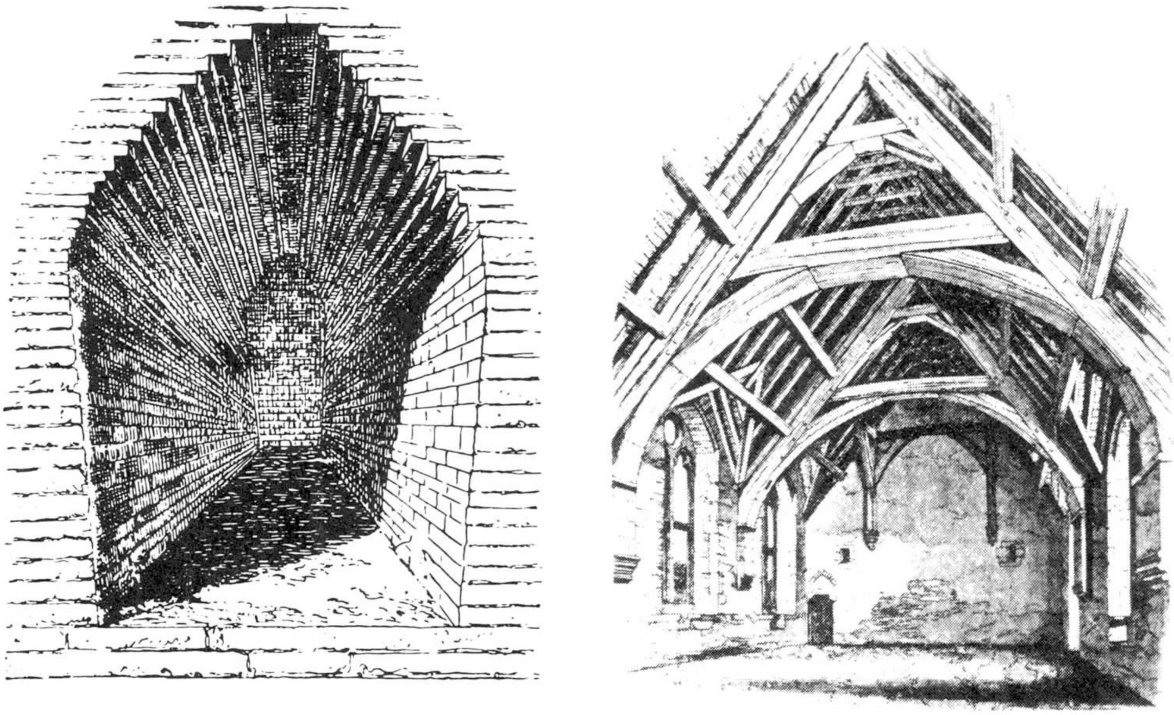

Fig. 1: Stone arches, timber structures

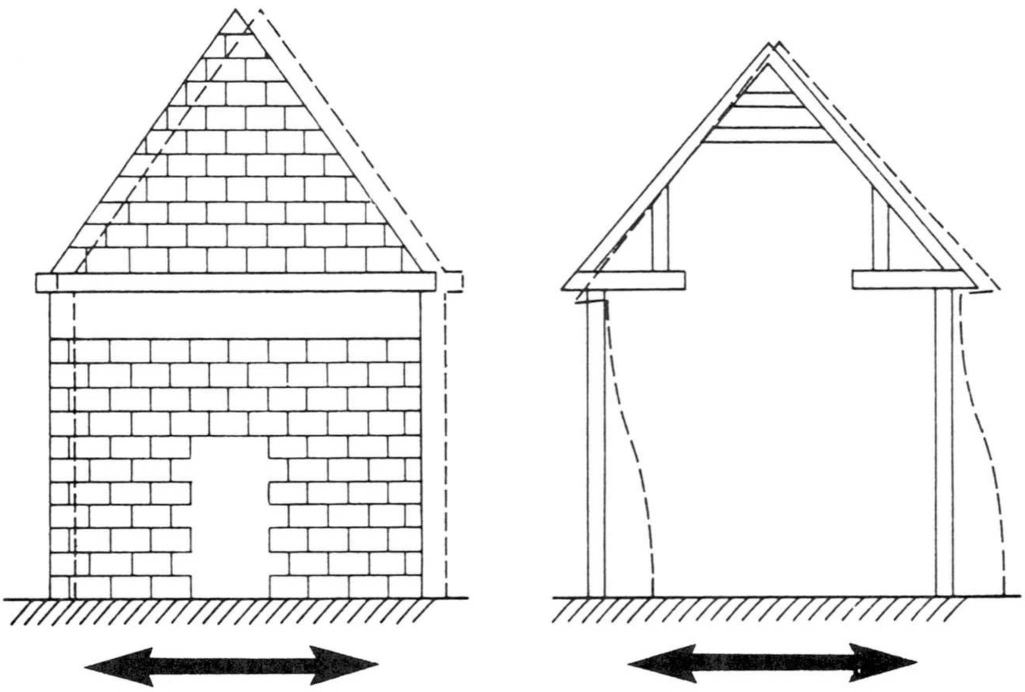

Fig. 2: Earthquake response of stone and timber structures

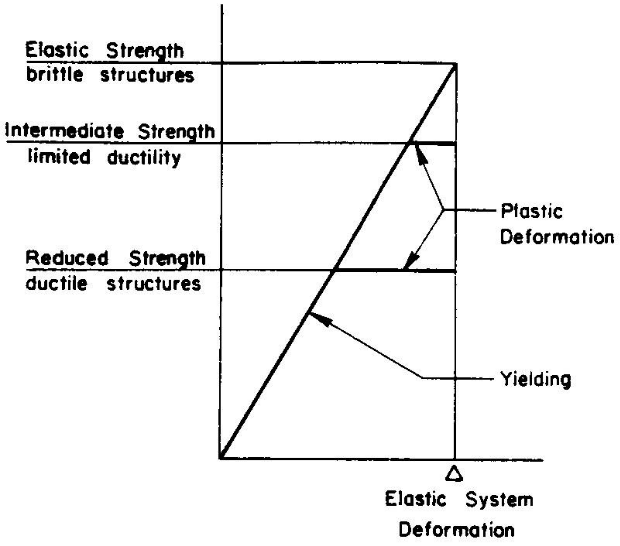

Fig. 3: Strength vs. deformation in elastic and inelastic structures

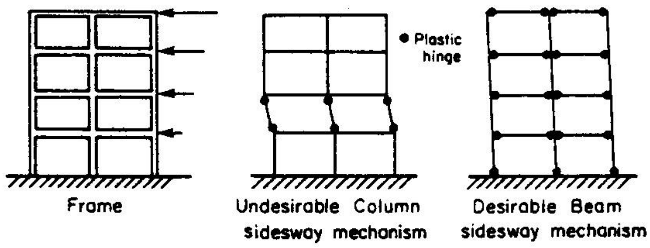

Fig. 4: Possible mechanisms due to formation of plastic hinges in frames subjected to lateral loads.

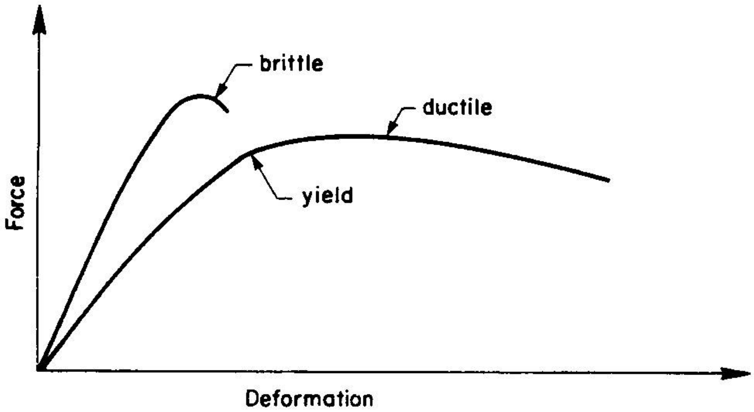

Fig. 5: Brittle and ductile failure mechanisms

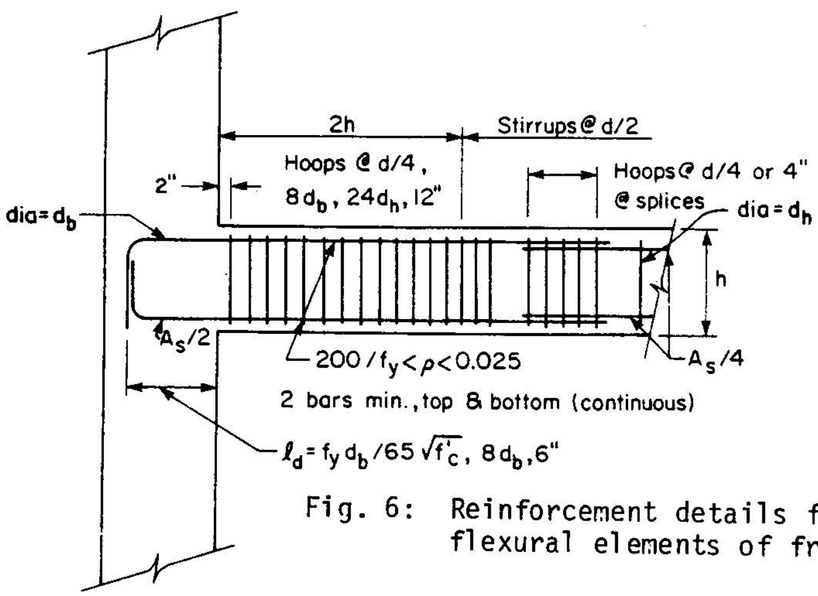

Fig. 6: Reinforcement details for flexural elements of frames

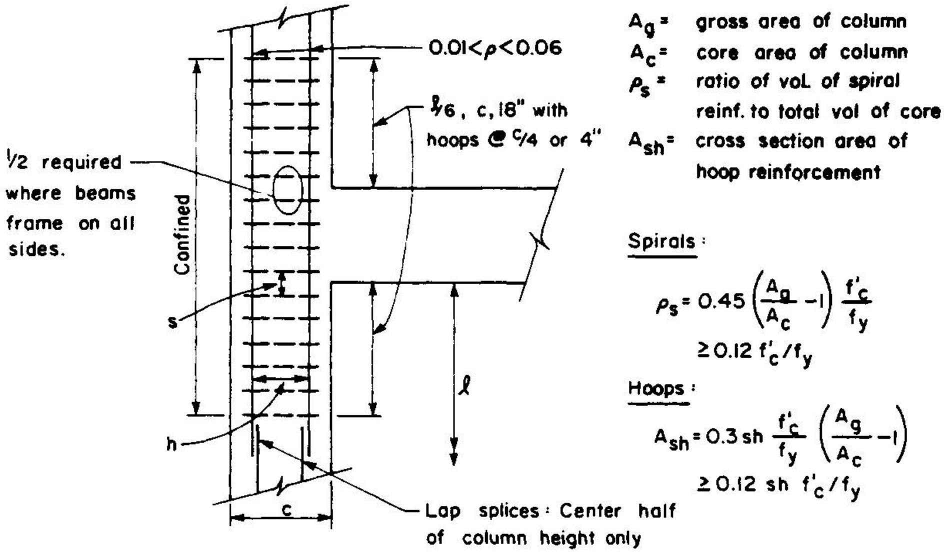

Fig. 7: Reinforcement details for columns of frames

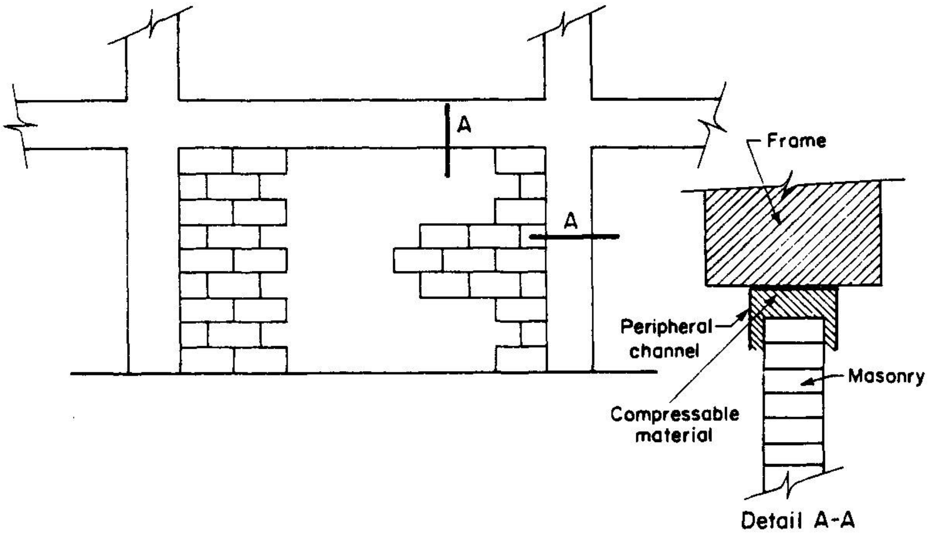

Fig. 8: Connecting rigid partitions into flexible frames

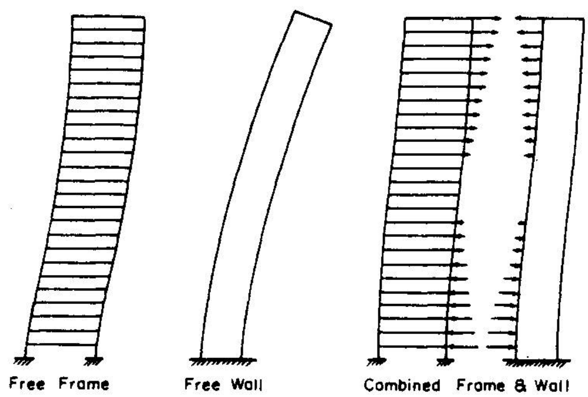

Fig. 9: Shear wall-frame interaction

Fig. 10: Damage to nonstructural elements in 1967 Caracas, Venezuela earthquake

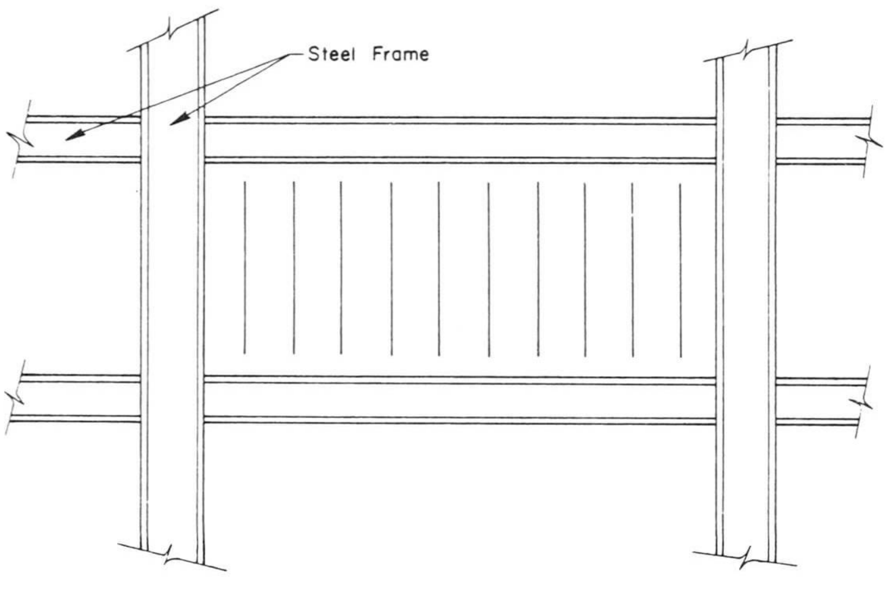

Fig. 11: Slitted walls