2.4 - BEHAVIOR OF SYSTEMS

by

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SYNOPSIS

Structural systems discussed in this report are the reinforced concrete, prestressed concrete, steel, mixed steel and concrete, and masonry structures. General performances of these structural systems under the earthquake disturbance, such as the hysteretic behavior, energy dissipation capacity and ductility, are discussed in connection with the design problems, with referring to the research work done in the past. Further investigations needed and the problems left to the future study are pointed out in regard to the design.

I. INTRODUCTION

Response of System to Earthquake

A general building structure is composed of structural elements, such as beams, columns, shear walls, vertical braces, etc. In addition, involved in the structure are slabs and claddings which may be non-structural walls, light-weight partitions, window-sashes, etc. The term "system" is regarded as an assemblage of the structural elements.

In order to know the behavior and performance of a structural system subjected to the ground motion, it is at least needed to clarify ; 1) the restoring force characteristics of the system, 2) the dynamic behavior of the system, and 3) the deflection behavior of each element involved in the dynamically behaving system. In this introductory study, the problems concerning the restoring force characteristics of the system are mainly discussed.

Element and System

The deflection behavior of an overall system is substantially affected not only by the behavior of beam and column elements but also by the behavior of connections, shear walls and vertical braces. The structural effect of slabs is usually considered as a diaphram action. It is often the case that their resistance together with beams against bending is neglected, or it is taken minimal if considered. However, attention should be paid on the fact that the mode of failure of the overall system may change due to the slab action. In some of the high-rize buildings, the details of connections between the structural and non-structural elements are designed in such a way that the latter shall not restrain the deflection of the former. However, in the real cases, both elements behave and deflect together, and therefore, the real deflection often differs from the computed value based on the assumption that the designed load is totally carried by the structural elements only.

The effect of thin reinforced concrete interior walls and partitioning walls made of concrete blocks or bricks cannot be neglected when the overall behavior of the system is considered, since they have relatively large stiffness and strength. It is necessary to develop an adequate connection detail between the structural and non-structural elements, and to strengthen the structural elements whose early failure may be caused by the effect of

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the non-structural elements. It is also necessary to give an adequate evaluation to the effect of light-weight partitions and window-sashes, although their stiffness and strength may be small.

Assesment

Several different assessments to clarify the behavior of the system have been found as follows :

Measurements during Earthquake and Investigation of Damage. A strong earthquake may be regarded as an experiment. Many information has been obtained from the damages caused by the past earthquakes, which could check the adequacy of the model tests being carried and of the mathematical models taken for the analysis. Recently, a quite large number of strong motion accelerographs are installed in the building and other structures in the earthquake area. In fact, a great deal of useful data were obtained from St. Fernand Earthquake. On the other hand, the data of the structural behavior under the medium or small size earthquakes record in the existing buildings have been analysed to know the transmission mechanism of the earthquake force from the ground to the structure [1]. From these field investigations, it has become known that the real behavior of the structure under the slight ground motion may differ substantially from the computed resuts, depending on the treatment of non-structural elements such as claddings. The effect of non-structural elements is expected to play more important role under the strong motion.

Full-Scale Tests. It is the best to investigate the behavior of the system by performing the full-scale test, but however, this is very rare because of the difficulty of the test. An example of the full-scale model test can be found in Japan, that was of a mass-produced reinforced concrete apartment building whose structural system was quite difficult to analyse [2]. Very few full-scale model test of steel structures was found, but a study of the test data in detail has provided many of new findings [3].

Model Test Using Shaking Table. The method to simulate the structural behavior under the earthquake motion by a model frame on the shaking table has become popular. Experimental studies on reinforced concrete and steel frames have been carried out in the University of Illinois and the University of California, Berkeley. A large-scale model test is not possible because of the capacity of the shaking table, and therefore it becomes necessary to test nearly full-scale models by dynamic hydraulic jacks.

Static and Dynamic Test and Analysis. Although the earthquake force is repetitive, it is often the case that the structural model is tested under the monotonic loading condition to investigate the basic behavior. The test data obtained in such a way are naturally not sufficient, since the strength and ductility of the structure would considerably differ under the repeated loading condition.

When the hysteretic behavior of the structure is to be investigated by the repeated loading test, one of the problems may be how to select the most appropriate loading program. Investigations reported in the past have often taken the loading programs in which the displacement amplitude is kept constant, or is gradually increased until the failure takes place. However, the input force to the structure during the real earthquake motion is naturally more random and complex, and the structural behavior may depend on the loading program taken in the test. An answer to this problem can be found in the work being carried out in the University of Tokyo [4], where the real structural behavior is simulated by connecting the structural model test with the computer which performs the dynamic analysis simultaneously. The model test is carried out semi-statically, because of the consuming time of the computer. Recently, the dynamic loading test has been frequently done by using the servo-type hydraulic jack. This type of test is quite useful, but however, in general, the accuracy and the number of measurements are limited in the case of the dynamic test. Therefore, experimental investigations should be based mainly on the semi-statical test, and the results of the dynamic test should be utilized to fulfill the gap between the statical and dynamic behaviors of the structure, such as the effect of the loading rate.

The method of analysis of the framed structures has been highly developed, and the load-deflection relationship of a simple steel frame can be very accurately obtained from the moment-curvature relationship computed based on the real stress-strain relationship of the material. The analysis of the complex frame requires the large capacity of the computer, and thus the analysis based on the plastic hinge concept is often performed. A similar method is also applied on the analysis of reinforced concrete framed structures, but some problems such as the shear deformation of the member and the deformation of the connection panel related to the slip of reinforcements are yet to be solved. Finite element method is quite popularly taken for the analysis of frames with shear walls.

Ductility and Energy Dissipation Capacity

The horizontal load-displacement relationships of two types of frames-ductile and brittle-are schematically shown in Fig. 1. The failure due to the shock of the strong earthquake is less possible in the frame shown in Fig. 1(a), which dissipates more energy at a certain displacement, than that in Fig. 1(b). A sudden reduction of the strength as shown in Fig. 1(b) may be caused by the shear failure of short columns and shear walls, and the flexural failure of columns carrying too large axial load in case of reinforced concrete structures, and by the local and lateral-torsional buckling of members, the buckling of braces and the fracture around the connections in case of steel structures.

Figure 2 shows the hysteretic load-displacement curves. The curves shown in Fig. 2(a) indicate the large loop area in one cycle of loading, i.e., the large energy dissipation capacity. On the other hand, the behavior in Fig. 2(b) shows the small capacity and the large reduction of the strength after the maximum strength is attained. Therefore, the displacement of the frame in Fig. 2(a) will be smaller than that of the frame in Fig. 2(b), if they are subjected to the same earthquake motion. The behavior shown in Fig. 2(a) may be observed in reinforced concrete frames whose beams and columns are designed below the balanced reinforcement ratio and fail in flexure, and in steel frames which are safely designed against the substantial strength reduction due to instability and connection fracture. The behavior in Fig. 2(b) can be seen when the shear failure occurs in the columns of reinforced concrete frames and in the shear walls of reinforced concrete core-systems, and when the buckling of braces, and local and lateral-torsional buckling take place in steel frames in the early stage of loading.

Formulation of Hysteresis Loops

As shown in Fig. 3, the real frame is often replaced by an equivalent multi-mass system, when the dynamic response of the frame to the arthquake motion is to be analysed, and it is required to formulate the hysteretic relationship between the story shear and displacement. Figure 4 shows some of the mathematical models of the hysteresis loop [5]. In addition to the frequently used bi-linear, tri-linear and Ramberg-Osgood-Jennings types shown in Figs. 4(a) to (d) respectively, the degrading model in Fig. 4(e) is assumed for a reinforced concrete frame in which the bending deformation is predominant. Several proposals can be found for the formulation of the S-shape hysteresis loops, which is assumed for a reinforced concrete frame involving many of the shear-failing members, and for a steel frame with relatively slender braces.

Deterioration of Strength due to Repeated Loading

Figure 5 shows an example of the deterioration of strength of a structure subjected to the repeated loading, the displacement amplitude being kept constant. This phenomenon can be seen in the shear wall systems and reinforced concrete frames involving members failing in shear or due to the slip of reinforcements. It is also observed in steel frames when the braces buckle or the local and lateral-torsional buckling of members take place.

II REINFORCED AND PRESTRESSED CONCRETE SYSTEMS

The category of the reinforced concrete type structure involves the following structural systems : framed structures of beams and columns ; framed structures having shear walls and slabs ; prefabricated structures ; and prestressed concrete structures. Full surveys have been made by Park [6] and Bertero [7] on the theoretical and experimental work on the reinforced and prestressed concrete frames under the repeated loading.

Framed Structures

Figure 6 shows the hysteresis loops obtained by testing a part of a school building frame. Columns in Fig. 6(a) are relatively slender and fail in flexure, while those in Fig. 6(b) are stubby and fail in shear [8]. The analysis of such a system composed of linear members is relatively easy. For the computation of the hysteresis loops, it is needed to know the deflection behavior of members and connections. For this purpose, subassemblages shown in Fig. 7 have been tested. The method to compute the flexural deflection of a member is already established to a certain extent, that is, the load-deflection relation of the system can be computed from the relation between member end moments and rotations, which depends on the moment-curvature relation of the cross section determined from the stress-strain relation of the material. In case of reinforced concrete structures, the deformation analysis taking only the flexure into account is not sufficient, since the deformation is affected by the following parameters : 1) shear deformation of members ; 2) slip of reinforcements ; 3) shear cracks in connection panels ; 4) slip of reinforcements going through the connection panel ; 5) deterioration of the bond strength of reinforcements anchored in the connection panel due to the repeated loading ; and 6) P-Δ effect in slender columns. Problems related to these parameters are yet to be solved. Most of the analysis found in the literature are limited to the point of the maximum carrying capacity, but however, it is needed, for judging the earthquake resisting ability, to investigate the behavior after the maximum carrying capacity is attained. It is also needed to analyse the three-dimensional behavior of frames, although most of the theoretical analysis reported as far have dealt with the plane frames. The overall failure of a frame is sometimes connected to the shear failure of columns, which are designed as long columns but in fact behave as short columns because of the effect of partitioning made of concrete blocks or bricks. Thus, the effect of non-structural elements must be more investigated.

Frames with Shear Walls

The behaviors of infilled frames and frames composed of plate-columns are different from those of pure frames. In case of multi-story shear wall systems shown in Fig. 8, the overall flexural deformation becomes large, compared with the pure frame. In such system, the stresses for the design, computed on the basis of the perfect elasticity, are sometimes unrealistic, because the initial rigidity and the rigidity after the cracks take place are substantially different between shear walls and surrounding frame. In addition, the effect of the rotation of the foundation cannot be neglected. The experimental research on the systems shown in Figs. 8(a) and (b) has been recently conducted, but the theoretical analysis of the hysteresis loops remains yet to be done. Investigations on the reinforced concrete braced frames point out the importance of the anchoring details of tension reinforcements.

Slab-and-Wall Systems

The analysis of the slab-and-wall system is quite difficult, compared with that of the structure composed of linear members. An appropriate method of analysis must be found. Figure 9 shows the experimental results obtained from the full-scale test of an apartment building frame [2].

Prefabricated Reinforced Concrete Structures

Reinforced concrete systems, composed of plate elements, box units, or linear members, have been prefabricated. In the prefabricated systems, the rigidity and strength of joints, which are cast in place, are less than those of the monolithicly constructed joints. Details of joints must be more investigated by testing the overall prefabricated structures.

Prestressed Concrete Structures

The energy dissipation capacity of a prestressed concrete structure is less than that of a reinforced concrete structure, in the range of the small deflection, since its behavior mainly remains in the elastic range. On the other hand, when they behave inelastically in the large deflection range under the repeated loading, the energy dissipation capacities of both structures become nearly equal. However, it must be noted that the failure often takes place at connections of a prestressed concrete structure. Experimental study on prestressed concrete systems is very few. The effect of prestressing on the earthquake resisting ability of the system must be experimentally investigated.

III STEEL SYSTEMS

Rigid frame systems of steel, often found in the high-rize buildings, can be categorized into unbraced and braced frames. In addition, there are some special systems, such as the core system which involves the reinforced concrete core, the staggered system, and the tube system. In general, these structural systems are mainly composed of linear members, and their structural behaviors are clear and easy to analyse, compared with the monolithic reinforced concrete structures. The behavior of steel frames under the repeated loading was surveyed by Wakabayashi [9] and Fujimoto et al. [10].

Unbraced Frames

Figure 10 shows the load-displacement relations of steel frames subjected to the constant vertical and monotonically increasing horizontal loads As seen in the figure, the negative slope of the load-displacement curve appearing in the large displacement range changes with the intensity of the vertical load, due to the P-Δ effect. The analysis of a highly redundant frame is often based on the plastic hinge concept, since a large amount of computation is required in the numerical integration method based on the moment-curvature relation of the cross section which is determined from the stress-strain curve on the material, and thus it is applicable only to a simple frame.

The hysteresis loops of a frame subjected to the alternating horizontal load become usually the spindle-shape as shown in Fig. 11 [11]. The effect of the vertical load on the shape of loops is as shown in Fig. 12 [9]. When the vertical load is large and the failure occurs in columns, not only the negative slope due to the P-Δ effect appears, but also the loop enlarges gradually due to the effect of strain-hardening. This phenomennon has been theoretically proved in the recent studies. For both cases in Fig. 12, the plastic hinge method of analysis can estimate well the experimental results. The local buckling takes place in the large displacement range. Although the deterioration of the hysteresis loops due to the local buckling seems to be not very significant if the lateral buckling is prevented, the post-buckling behavior of a member must be theoretically analysed in order to estimate the frame behavior in the large displacement range. This problem is left to the future investigation, and only the answer to this problem can provide the theoretical basis of the specification concerning the width-to-thickness ratio of a plate element. The effect of the torsional action of an overall frame, which is, for example, caused by the eccentrically located core, is one of the important problem, but the investigation on the space frames is very few. Figure 13 shows the experimental results of a simple space frame. Members involved in a space frame are subjected to biaxial bending and torsional moments in addition to the axial thrust, and the yield condition and associated flow rule become complex.

Braced Frames

The restoring force of a braced frame is approximately equal to the sum of those provided by the brace and the unbraced frame. The behavior of the braced frame is more similar to that of the brace than that of the unbraced frame, since the horizontal stiffness and strength of the former are much larger than those of the latter. A very slender brace does not carry the compression force, and its hysteretic behavior is as shown in Fig. 14(a). When the repeated load is applied with the deflection amplitude kept constant, it does not dissipate any energy as shown in Fig. 14(b)[12]. In case of braces with the medium slenderness ratio, the shape of hysteresis loops depends on the slenderness, as shown in Fig. 15 [13]. Shown in Fig. 16 are the hysteresis loops of a braced frame obtained by combining those of the brace and unbraced frame [14].

The behavior of the brace has been investigated in Japan, U.S.A. and Italy, and become quite clarified. The problem left to the future study is how to connect the theoretically formulated brace behavior to the static and dynamic analysis of the more complex frames.

IV MIXED STEEL AND CONCRETE SYSTEMS

Types of beam and column sections involved in a mixed steel and concrete structure are as follows : beams = encased steel in concrete, composite concrete and steel, bare steel, and reinforced concrete ; and columns = encased steel in concrete, concrete filled steel tube, bare steel, and reinforced concrete. In general, members of rolled steels or steel tubes are ductile compared with reinforced concrete members. However, examples of the brittle failure can be easily found also in the mixed members, such as a shear failing encased steel column with batten plate type open-web. Investigations on the mixed structures are less than those on steel or reinforced concrete structures.

Encased Structures

In Japan, the encased structure is often referred to as the "SRC" (steel reinforced concrete) structure, and a quite popular structural system. However, only a few experimental work on the encased steel frames has been done. The deflection behavior of an encased steel structure failing in flexure is quite similar to that of a reinforced concrete structure which is obtained by replacing the steel used in the former by an equivalent amount of main reinforcements. When they are subjected to the repeated loading in the large displacement range after the maximum strength is attained, the encased structure shows the more ductile behavior. Also, the shear failing encased structure is more ductile than the reinforced concrete structure, if the steel members encased in concrete have the full-web or truss type open-web. Figure 17 shows the behavior of portal frames failing in flexure under the monotonic horizontal load [15]. The maximum strength of the frame subjected to the vertical load equal to 40% of the maximum column strength under pure compression is higher than that of the frame under the zero vertical load. However, the steeper negative slope appears due to the P-Δ effect and the reduction of the moment capacity in the cross section in the large curvature range. Figure 18 shows the experimental results of encased frames with full-web steel members under the alternating horizontal load [16]. The frame under the zero vertical load shows the sufficiently ductile behavior, and the ductility becomes lesser with the increase in the vertical load. A very brittle failure is observed in the frame subjected to the vertical load equal to 60% of the maximum column strength. For comparison, reinforced concrete frames were tested, and the results are shown in Fig. 19. The frames failed in flexure, and it is observed that the ductility of the reinforced concrete frame is less than that of the encased steel frame, both being subjected to the vertical load equal to 30% of the corresponding maximum column strength. It is needed to investigate the limit of the design axial load in columns in order to guarantee the sufficient ductility. It is also needed to clarify the shear deformation of the beam-to-column connection panel, and the effect of the slip of reinforcements.

Steel Structures with Composite Beams

Figure 20 shows the test results of a steel frame in which concrete slabs cast on steel deck plates are connected to beams by shear connectors [3]. The hysteresis loops show the spindle-shape, and the sufficient ductility. The strength is not very much deteriorated even after the local buckling takes place. The theoretical hysteresis loops agree well with the experimental results. Further investigation is needed on the effect of the slab in this type of structures.

Prefabricated Encased Structures (HPC)

Prefabricated encased structural systems are often used in the construction of apartment buildings of 10 to 15 stories in Japan [17]. The plan of such a structure is usually rectangular. The horizontal load acting in the direction of the longer span is resisted by a rigid framing system of beams and columns, and that in the other direction is resisted by precast concrete shear walls in which steel plates assembled like a truss are encased. Many investigations have been performed on this type of shear walls, and it has become known that they have the sufficient strength and ductility if the detail is carefully designed. It is necessary to guarantee the sufficient strength in reserve for the connections of the precast panels such as a slabs and shear walls.

V MASONRY SYSTEMS

Brick structures and concrete block structures are usually designed in such a way that the walls in the direction of the earthquake force resist the shear, and the walls in the other direction resist the out-of-plane bending (Fig. 21). Experimental studies have been carried out in order to clarify the shear strength of the wall with or without openings, and the flexural strength of the wall subjected to the out-of-plane force. Full-scale test or model test of three-dimensional masonry structures are needed to investigate the interaction between the walls in two directions and the behavior when the load is applied in an arbitrary direction.

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FIGURES

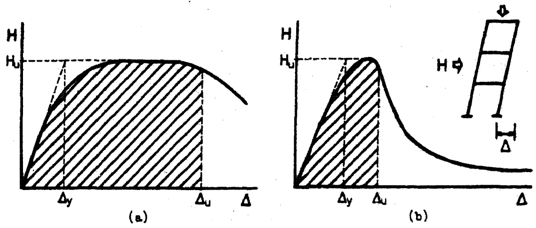

Fig. 1 Energy Absorption Capacity of Frames

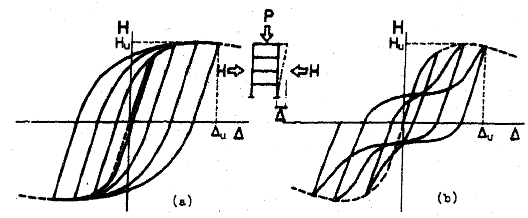

Fig. 2 Hysteresis Loops of Frames under Repeated Horizontal Loading

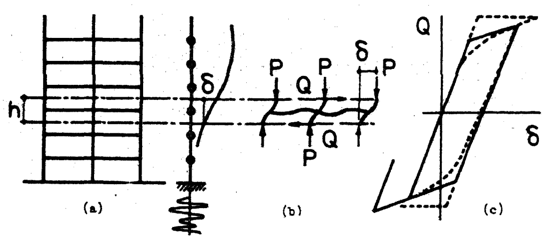

Fig. 3 Mathematical Model of a Frame

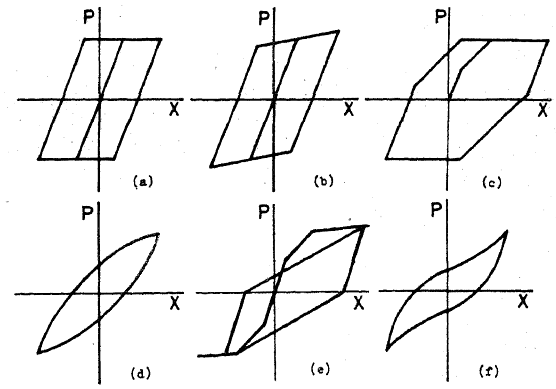

Fig. 4 Idealized Hysteresis Models

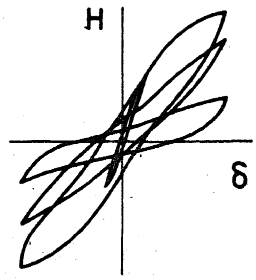

Fig. 5 Deterioration of Strength

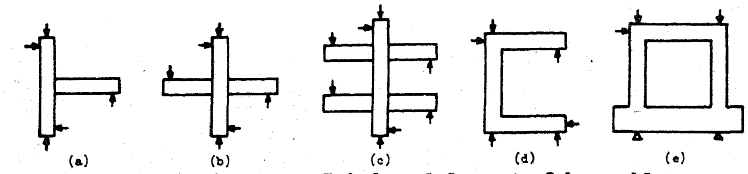

Fig. 7. Experiments on Reinforced Concrete Subassemblages

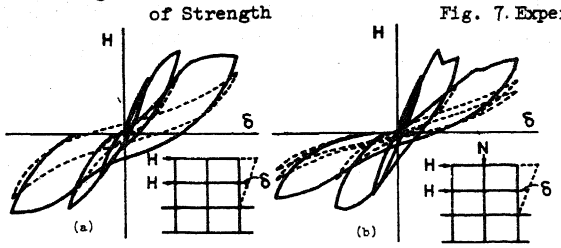

Fig. 6 Hysteresis Loops of Reinforced Concrete Frames

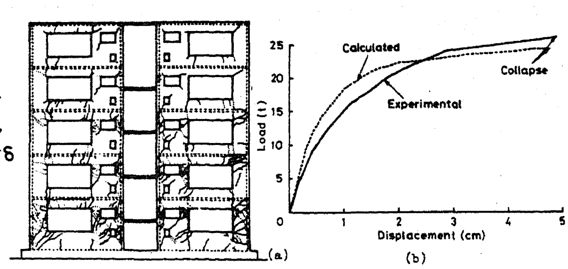

Fig. 9 Full-Scale Test Results of a Shear Wall Type Apartment

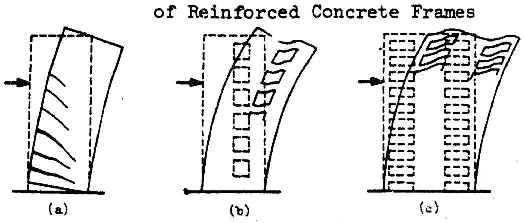

Fig. 8 Multi-Story Shear Walls

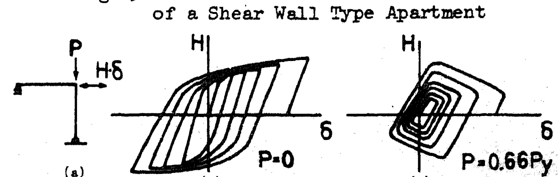

Fig.12 Hysteresis Loops of Steel Knee-Bents

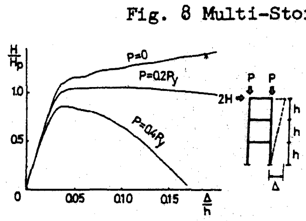

Fig.10 Steel Frames under Constant Vertical and Monotonic Horizontal Loads

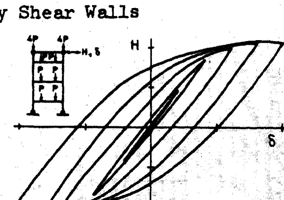

Fig.11 Hysteresis Loops of a 3-Story Steel Subassemblage

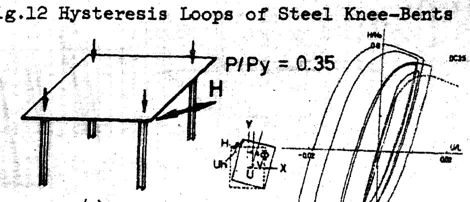

Fig.13 Hysteresis Loops of Steel Space Frame

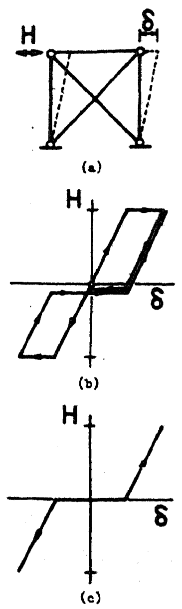

Fig.14 Hysteresis Loops of a Bar Brace

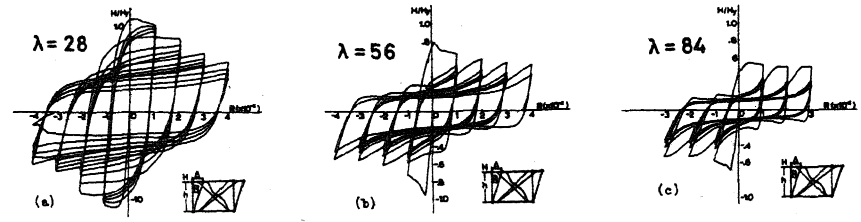

Fig.15 Hysteresis Loops of Steel Braces with Medium Slenderness

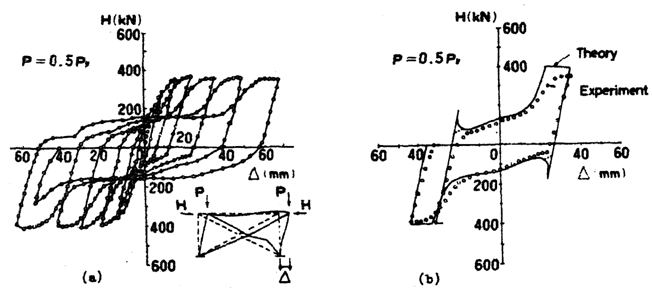

Fig.16 Hysteresis Loops of a Full-Scale Braced Frame

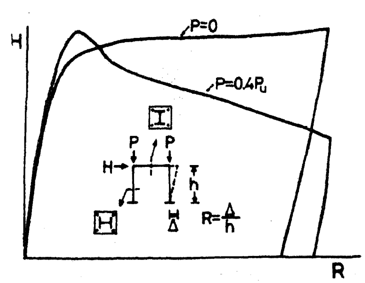

Fig.17 Load-Displacement Curves of Encased Steel Frames

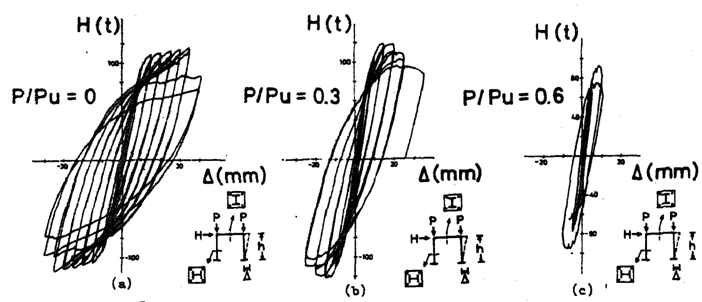

Fig.18 Hysteresis Loops of Encased Steel Frames

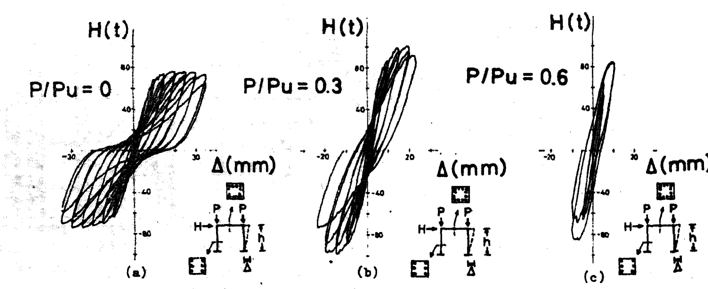

Fig.19 Hysteresis Loops of Reinforced Concrete Frames

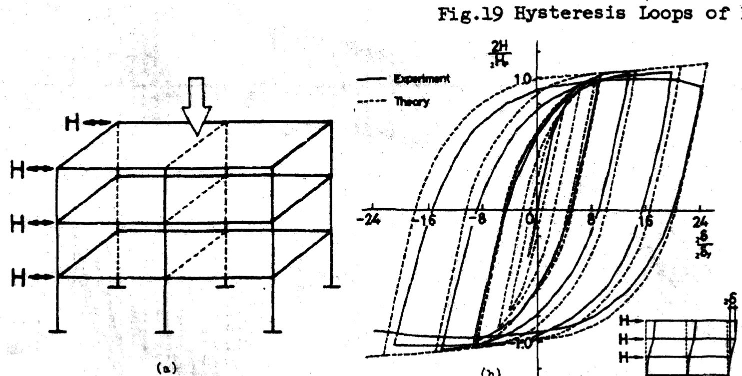

Fig.20 Hysteresis Loops of Full-Scale Steel Frames with Composite Beam

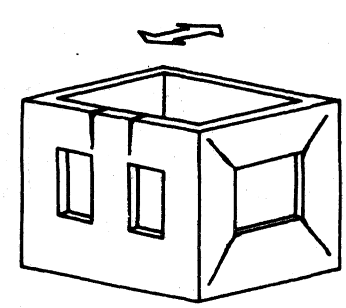

Fig.21 Load Effect on a Masonry Structure

DISCUSSIONS

S.C. Gupta (India)

It is generally stated that structural systems using shear walls with frames are better from earthquake resistant point of view. However such systems are much more stiff as compared to ductile frame systems and develop much higher overturning moment at the base when subjected to same accelerogram. This gives a feeling that systems with shear walls are not suitable for sites having poor soil conditions. I request for the views of Prof. Wakabayashi on this aspect.

P. Dayaratnam (India)

Can we recommend same limit of lateral deflection or drift to all kinds of building such as concrete frame buildings, buildings with shear walls, and buildings of shear wall and frame. The damage to concrete for same drift limitation for different type of buildings is likely to be different even though the psycological effects may be same. Can we suggest a drift limitations for different type of buildings.

Author's Closure

For high rise building, the use of shear walls may not produce economical results, as the increase of natural frequency of a building may result in larger overturning moment. For strengthening building frames without increasing their rigidity too much, special types of shear walls like slitted shear walls are used in some countries.

It is expected that this shortcoming mentioned above may be overcome in general case, as the increase in strength of a building to lateral force by placing shear wall is so large. Especially, in the case of low rise buildings the increase of natural frequency does not mean the increase of input energy, because the peak frequency of earthquake motions may be larger or smaller than the fundamental natural frequency of the building. Not like the case of high rise building, the earthquake resistance capability of building will be increased by the increase of radiational damping if the rigidity of a building on soft ground increases.

Special attention must be paid to provide strong foundations to prevent differential settlements during the earthquake motions and to minimize torsional deformations due to inappropriate arrangement of shear walls, when shear walls are used.

The drift limitation is closely related to the deformability of structures or ductility factor which vary with the types of structures. For instance, a reinforced concrete pure frame should have different value of drift limitation from that of a frame with shear walls, as they have different values of deformability each other.