ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 2, NO. 1, (2001)
PAGES 73-84

EARTHQUAKE RESISTANT DESIGN OF REINFORCED CONCRETE BUILDINGS

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ABSTRACT

This paper briefly reviews the development of earthquake resistant design of buildings. The state-of-the-art of seismic design is discussed from the viewpoint of the performance criteria of buildings. These are (a) serviceability from frequent minor-intensity earthquake motions, (b) reparability from an infrequent but major-intensity earthquake motion, and (c) life safety from the maximum possible earthquake motion. The relation between the strength and ductility is discussed in length. With the introduction of performance-based engineering, the importance of reparability and serviceability criteria is emphasized.

The concept of capacity design is outlined. A weak-beam strong-column mechanism is selected as an example of the target yielding mechanism for design.

Keywords: earthquake resistant building, design, reinforced concrete building, performance-based design, strength, ductility, capacity design, weak-beam strong-column mechanism.

1. INTRODUCTION

The reinforced concrete has been used for building construction since the middle of 19th century, first as a part of buildings and then as a whole structure. The construction always preceded the development of structural engineering. Dramatic collapses of buildings have been observed after each disastrous earthquake. Various types of damage were observed in the past. Each damage provides important information relevant to the improvement of design and construction practices. The development of earthquake resistant building design is briefly reviewed in this section.

John Milne, a British instructor at University of Tokyo, studied the damage of the 1891 Nohbi Earthquake, Japan, which killed 7,273. Heavy damage was observed in then-modern western brick construction in Nagoya area. Milne [1] noted, "... we must construct, not simply to resist vertically applied stresses, but carefully consider effects due to movements applied more or less in horizontal directions." A design seismic force was not quantified in his report.

The first quantitative seismic design recommendations were made after the 1908 Meson Earthquake, Italy, which killed more than 83,000. Housner [2] stated in his keynote address at the Eighth World Conference on Earthquake Engineering that "... M. Panetti, recommended that the first story be designed for a horizontal force equal to 1/12 the weight above and the second and third stories to be designed for 1/8 of the building weight above."

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Table 1 Major Damaging Earthquakes in Iran (Ref.1)

Year/Month/Day	Magnitude	Region	Deaths
856/12/22	6.5	Damghan	200,00
943/08/20	7.6	Nesa	5,000
1042/11/04	7.6	Tabriz	40,000
1336/10/21	7.6	Khaf	30,000
1405/01/29	6.7	Neyshabur	30,000
1440/---/---	6.5	Qir-Karzin	10,000
1673/07/30	6.5	Mashhad	5,600
1721/04/26	7.7	Tabriz	40,000
1780/01/17	7.7	Tabriz	200,000
1853/05/04	6.5	Shiraz	9,000
1893/11/17	6.6	Quchan	5,000
1909/01/23	7.7	Brujerd	6.000
1962/09/01	7.3	Boeinzahra	12,200
1968/08/31	7.3	Dashtbayaz	10,000
1972/04/10	7.1	Qir-Kariz	5,010
1978/09/16	7.7	Tabas	18,225
1990/06/20	7.7	Manjil	40,000

The design seismic forces were introduced in the Enforcement Order of Urban Building Law (Japan) in 1924 after the 1923 Kanto Earthquake Disaster, which killed more than 140,000. Seismic coefficient of 0.10 was used in an allowable stress design framework. The allowable stresses of concrete and steel were one-third nominal compressive strength and one-half yield stress, respectively. The 1927 Uniform Building Code (U.S.A.) adopted the same seismic coefficient after the 1925 Santa Barbara Earthquake. Although design seismic forces were introduced in the code, no simple and practical methods of structural analysis were available until the introduction of the moment distribution method by Cross [3] in 1930 and the D-value method by Muto [4] in 1933.

At this stage, researchers and engineers discussed the earthquake resistant building design without knowing the characteristics of earthquake motions. The U.S. Seismological Field Survey (later known as U.S. Coast and Geodetic Survey) was established in 1932 and installed the first strong motion seismographs in California. The famous El Centro records were obtained in 1940 during the Imperial Valley earthquake. Biot [5] and Housner [6] calculated the response of mechanical systems under recorded earthquake motions in 1941. The City of Los Angeles Building Code recognized different earthquake effects on building response with the number of stories in 1943. The Structural Engineers Association of California (SEAOC) [7] developed a seismic design model code in 1957.

Kawasumi [8] formulated a probability map of maximum ground accelerations expected in 100 years in Japan on the basis of historical data of earthquake occurrences. This was an important step to define an earthquake-zoning map for design.

With the development of digital computers, nonlinear earthquake response was calculated. Veletsos and Newmark [9] reported the relation between the maximum response of linearly elastic and elasto-plastic systems in 1960. Linearly elastic response spectra have been used in the seismic design to determine the required resistance of a structure for an estimated ductility

capacity. With an accumulation of experimental data, Takeda, Sozen and Nielsen [10] proposed a realistic hysteresis model for reinforced concrete members in 1970. Nonlinear response of reinforced concrete buildings could be calculated under earthquake motions.

An integrated design procedure, called Capacity Design, was developed for reinforced concrete buildings in New Zealand under the leadership of Paulay [11]. A clear hierarchy in failure modes should be outlined in the structural planning stage. The weak-beam strong-column failure mode is advocated. Each structural member must be proportioned to achieve the intended structural strength and deformation capacity under the ground motion.

Six European countries signed the Roman Treaties in 1957 to establish European Economic Community (present European Union). Committee European de Normalization (CEN) initiated a project to formulate Euro Codes in 1990. The codes will be commonly applied to the design and construction throughout the community. This was an important experiment to harmonize different ideas to establish a common concept on the basis of (a) Rationality, (b) Transparency and (c) Harmonization.

The SEAOC published "Vision 2000 - A Framework for Performance Based Engineering [12]" in 1994. The performance-based design intends to construct a building that satisfies the planned performance under a given set of loading conditions. Since the beginning of the twentieth century, earthquake engineering has been developed with a sole aim to construct safe buildings to protect human lives from earthquake disasters. It is time for us to design a building structure to maintain its function after an earthquake.

With this brief historical review, this paper discusses the earthquake resistant design of reinforced concrete buildings. Although the engineering appears to be uniform in the world, the design and construction of buildings are influenced by the culture, economics and technical environment of a society.

2. EARTHQUAKE GROUND MOTIONS

The recent development in seismology is fascinating; plate tectonics developed since the 1960s can explain the occurrence of earthquakes along the boundaries of tectonic plates. Relative movement of tectonic plates can be monitored with the use of the global positioning system (GPS). Seismically blank regions where next large earthquakes may occur along the tectonic plate boundary are identified. However, it is not possible at this stage to accurately predict the time, location and magnitude of an earthquake occurrence.

It is more difficult to predict earthquakes within a tectonic plate, such as the 1995 Hyogo-ken Nanbu earthquake in Kobe. These earthquakes are known to occur by the fracture of active faults, but an active fault fractures once in one to a few thousand years. Some faults have been identified on ground surface, but others are buried under the ground.

2.1 Earthquake ground motions

A seismometer to measure ground displacement during an earthquake was developed in late nineteenth century. The seismometer has been used by seismologists to understand the source mechanism of earthquakes, but it does not provide acceleration records necessary for engineering purpose. The seismologist believed that the acceleration signal was affected by accidental phenomena such as local geology.

A strong motion accelerograph to record ground acceleration was developed in the early 1930s. The characteristics of earthquake ground motions were studied through the observed

records; i.e., common features of acceleration records were abstracted and general shapes of response spectra were established for design purpose taking the local effect of soil into account.

Historical records about earthquake occurrences are studied to estimate the probability of the maximum earthquake intensity in a region. A large uncertainty exists in the estimated maximum ground acceleration attributable to the inaccuracy and the limited period of the historical documentation.

2.2 Engineering seismology

For the establishment of design earthquake ground motions specific at a construction site, the seismic history and the geometry of active faults, dynamic rupture process of earthquake sources, the modeling of underground structures and transmission of earthquake motions should be investigated. There have been efforts by engineering seismologists to estimate the characteristics of future earthquake motions. The global parameters (fault length, width and seismic moment) of future earthquakes can be estimated by the seismic history, geological investigation and source modeling of active faults near the construction site. The local source parameters (slip heterogeneity on fault plane) are important to characterize the fault movement along the slip plane, especially the slip and slip velocity. The local parameters cannot be evaluated theoretically, but must be determined by the source inversion of past major events with the use of statistical analysis. If the global and local parameters of an earthquake are identified, the motion at the identified active fault may be estimated. The transfer function from the source to the construction site may be estimated by an empirical Green's function; i.e., the transfer function of past small earthquakes in the region. Such a scenario for simulating earthquake motion from a target earthquake has been discussed after the 1995 Hyogo-ken Nanbu earthquake by engineering seismologists. Some of these methods are applied in the design of major construction projects in the United States and Japan.

It is important to recognize that seismic design of a structure is based on a large uncertainty about the characteristics of a design earthquake motion, especially intensity.

3. PERFORMANCE REQUIREMENTS OF BUILDINGS

A structure fails when the limit of its resistance is reached under external disturbance. A strong but brittle system and a weak but ductile system, shown in Figure 1, may equally survive an earthquake ground motion without collapse, as long as the maximum response does not exceed the failure point.

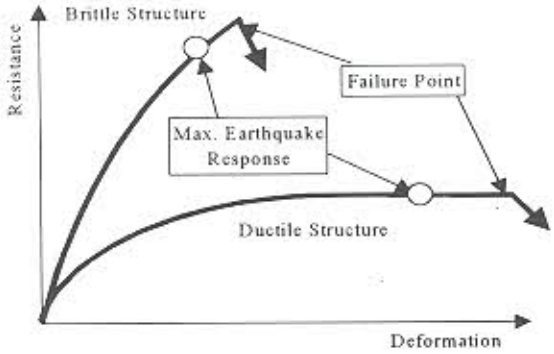


Figure 1: Earthquake resistance of structures

Since the 1960s, it has been believed that it is not feasible to design a building structure to remain elastic under intense ground motions. Therefore, seismic design has aimed that (a) the structure should not suffer any structural damage (serviceability limit state) from frequent minor earthquakes, (b) the structure, with the repair of damage, should be usable after an infrequent earthquake of major intensity, and (c) the structure should not collapse (life safety limit state) for the safety of occupants during the largest possible earthquake at the construction site.

3.1 Minimum strength and ductility

Figure 2 shows schematically the expected performance of a building under frequent, infrequent, and very rare earthquake motions. A certain minimum resistance is necessary to limit the damage from frequent minor ground motions. Architectural elements, such as non-structural curtain walls, partitions and mechanical facilities, must be protected for the continued use of a building after an earthquake.

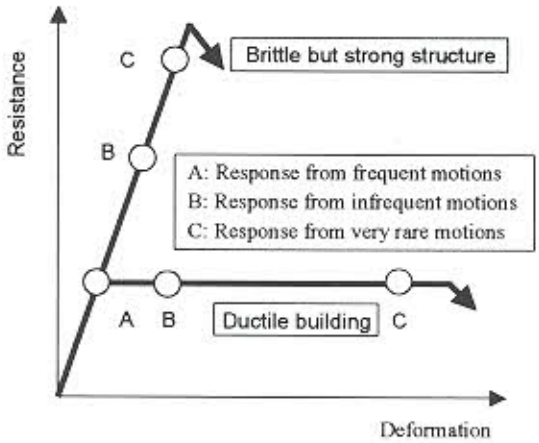


Figure 2 Performance objectives of building

For the prevention of collapse, high resistance is necessary for a brittle structure and low resistance may be allowed for a ductile structure. The high lateral force resistance can be achieved by the use of structural walls. The deformation capacity of a reinforced concrete building has been believed to be so small that sizable lateral resistance must be provided in design to limit the plastic deformation. Therefore, it is normally believed that a reinforced concrete structure can satisfy serviceability requirements, if the structure is designed to survive the maximum possible earthquake.

With understanding of reinforced concrete behavior, however, good reinforcement detailing has been enforced in design and construction to enhance the deformation capacity. Therefore, a reinforced concrete building is sometimes designed with low lateral resistance counting on ductility. It becomes essential that a structural engineer should examine the serviceability limit state from frequent but low-intensity earthquake motions and the level of structural damage from infrequent but major-intensity earthquake motions.

3.2 Design seismic forces

The lateral force resistance of a building is required in a building code, taking into account (a) seismic risk, (b) soil condition at construction site, (c) building period, (d) anticipated ductility and acceptable level of damage in a building, and (e) structural irregularity. The level of minimum lateral resistance should be determined (a) to control the serviceability of buildings from frequent earthquake motions and (b) to protect the occupant's life by limiting the nonlinear deformation from the maximum possible earthquake motion.

It should be noted that the building code normally outlines the minimum standard required in the society. The expected performance (minimum required strength and acceptable damage) of buildings varies from a country to another because each country has different levels of (a) seismic risk, (b) hazard tolerance, (c) economic background, and (d) technical development. The function or the importance of a building should be considered in selecting the acceptable level of damage.

The design must satisfy, in addition to the minimum code requirements, the performance requirement set up by a building owner. The recent performance-based engineering emphasizes the protection of function in a certain kind of buildings for the continued operation and usage after major earthquake motions. This is important in design and construction of, for example, hospitals, computer and information centers, and disaster management facilities. The use of higher design earthquake forces may reduce the structural damage, but it is not sufficient to protect the function of the building. New technology such as base-isolation and energy dissipating devices and auto-adaptive media is available to achieve the purpose.

3.3 Reparability and structural walls

During the twentieth century, earthquake engineering devoted to the development of technology to protect human lives from earthquake disasters. The importance of ductility has been emphasized for the survival of a building. It should be noted that the "ductility" is the ability of a structure to sustain the resistance after developing plastic deformation. The ductility is certainly important for survival of a building under an extraordinary earthquake motion. However, the damage will develop in a building even during infrequent earthquake motions if the ductility is assumed in design. There exists a wide gap in the intensity of the strongest possible and frequent earthquake motions. The damage must be repaired after frequent earthquakes as well as the strongest possible earthquake.

The reparability is recognized to be an important limit state in the performance-based engineering. The cost of repairing structural members after an infrequent earthquake may reach the construction cost of a new building. A structural engineer should advise a building owner about possible cost for repair and loss associated with the closing of his/her building operation during the repair work if a building is designed with low lateral resistance's counting on a large ductility of the structure.

The damage level of structural and non-structural elements is known closely related to story drift (inter-story deformation) of a building. The structural damage of a brittle but high resistance building (Figure 2) is much smaller under a very rare or frequent earthquake motion than the damage of a ductile structure. A number of damage investigations reported the effectiveness of structural walls in reducing the damage in structural members as well as non-structural elements. It is worth noting that a significant damage could be repaired using present state of construction technology. An expensive and difficult repair work may be necessary if, for example, the reconstruction to the original configuration is not permitted by the revised city ordinance. The technical reparability is not necessarily dependent on the damage level, but is rather governed by

the necessity of the building owner.

3.4 Vertical irregularities

A large earthquake response tends to concentrate at flexible and weak stories. Severe damage and collapse of soft first-story buildings were reported in past earthquakes, especially in the 1995 Kobe earthquake disaster. In a multi-story residential building, the first story was often used as commercial facilities or garages where structural walls placed to separate residential units above were discontinued. A large base shear must be resisted by first story columns, which caused a large story drift concentrated in the first story and failed the columns having limited deformation capacity due to heavy axial forces. It should be noted that exterior columns are subjected to large variation of axial forces induced by overturning moment due to lateral forces acting on a building. This additional axial force further reduces the deformation capacity of the columns.

Middle story collapse was observed in moment resisting frame buildings in Kobe. This type of collapse was observed in relatively old construction where columns failed in a brittle shear mode. The improvement in shear design of reinforced concrete members is believed to prevent the mid-story collapse.

3.5 Horizontal irregularities

The eccentricity between the centers of mass and stiffness causes torsion vibration during an earthquake, causing larger damage in members away from the center of stiffness. Well-balanced placement of stiffer and stronger members should be considered in a plan.

3.6 Non-structural Elements

The non-structural elements are essential part of a building function. Non-engineer residents of a building may be greatly scared by the damage of non-structural elements, such as partitions, windows, doors and mechanical facilities. The building may not be occupied until the damaged non-structural elements are repaired or replaced. The cost of repair work is often governed by the replacement of the damaged non-structural elements rather than the repair work on structural elements. The non-structural elements must be protected from damage to reduce financial burden on the building owner.

Non-structural elements must be also protected from damage because the fall of failed elements is dangerous for people escaping from the building and because the failed elements may block evacuation routes in a severely damaged building.

Controlling inter-story drift by the use of structural walls or improving the method to fasten the non-structural element to the structure may reduce the damage of partitions. Stiff, weak and brittle brick walls, filled in a flexible moment-resisting frame, fail at an early stage even during medium-intensity earthquakes. Providing some gap on both side of a column could reduce such damage.

The response (acceleration or velocity) of a structure must be controlled to prevent heavy furniture and equipment from overturning on the floor or to prevent heavy equipment from falling from shelves; otherwise the contents of a building should be properly fastened to the structure.

3.7 Retrofitting of existing buildings

The earthquake resistant design technology progressed significantly in the last few decades. The damage investigation has demonstrated the poor performance of older buildings designed using out-dated technology. The retrofit of deficient buildings is an urgent task of the owner; the

owner is responsible for maintaining the performance of his building to the existing code level. An efficient and reliable seismic assessment procedure should be employed to identify probably deficient buildings.

New structural walls may be added to enhance the lateral resistance of weak buildings as long as the foundation has sufficient capacity to support additional weight caused by the walls. Steel bracing's can be installed if the foundation has a problem. The ductility of columns can be improved by steel plate jacketing or carbon-fiber plastic sheet wrapping.

4. CONCEPT OF CAPACITY DESIGN

The capacity design philosophy is a general design concept to realize the formation of an intended yield mechanism. This concept has been commonly applied to the plastic design of steel structures in which large plastic deformation capacity is expected at yield hinges.

When the capacity design procedure is adapted to an earthquake resistant design of a reinforced concrete structure in a seismically active country, three problems had to be solved because the plastic deformation capability of reinforced concrete members is limited; i.e.,

(a) An acceptable form of yield mechanisms to minimize the plastic deformation demand from reinforced concrete members,

(b) Required lateral load resistance to control the response plastic deformation at critical sections within an acceptable level, and

(c) Required resistance of members not a part of the acceptable yield mechanism during an earthquake.

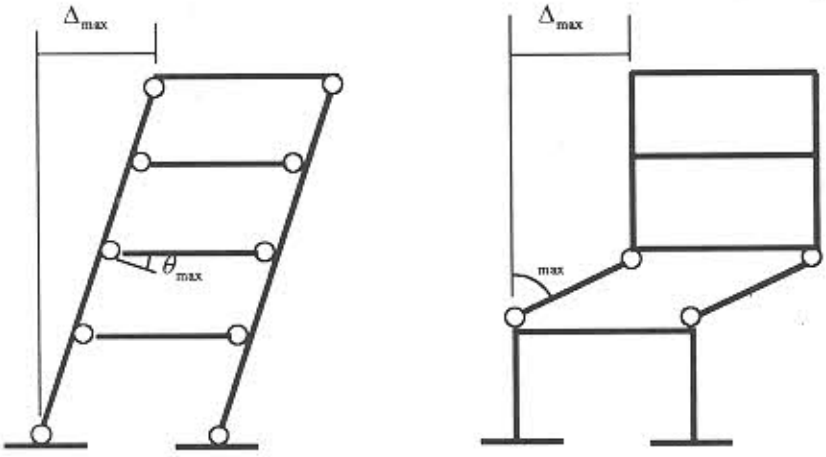
4.1 Weak-beam strong-column mechanism

Many structural engineers have preferred the weak-beam strong-column mechanism; i.e., a moment-resisting frame develops yield hinges at the end of girders and at the base of first -story columns and structural walls under an intense earthquake.Figure 3. The earthquake-input energy can be quickly dissipated by fat and stable hysteresis of flexural yielding at beam ends. For a given displacement of a structure, the ductility demand at yield hinges in the weak-beam strong-column structure is minimum because plastic deformations are uniformly distributed throughout the structure. It is also true that the deformation capacity is reasonably large in girder members where no axial force acts; on the other hand, the formation of a plastic hinge at the base of the first story column is not desirable because large deformation capacity is hard to develop at the locality due to the existence of high axial load. Some extra moment resistance should be provided at the base of the first story columns to delay the yield hinge formation. It is not desirable to form plastic hinge in columns, which cannot develop large deformation capacity.

The formation of yield hinges at the ends of roof-level girders is not desirable from the durability point of view; i.e., wide crack opening in girders and roof floor slabs may lead to water leakage after the earthquake. The design of roof-level girders is normally governed by the minimum reinforcement requirement, and it is easier to allow yield hinges to form at the top of top-story columns.

It should be noted that the fundamental mode of vibration governs the deformation response of low to medium-rise buildings during an intense earthquake; therefore, the weak-beam strong-column yield mechanism of a structure is assumed to form under the lateral force distribution similar to the fundamental mode shape of vibration. The mode shape does not change significantly even after the formation of plastic hinges in a structure of regular configuration.

However, sizable contribution of higher modes takes place in the displacement r ,ponse of high-rise buildings. Therefore, a special care should be exercised in selecting the distribution pattern of lateral forces for high-rise buildings.



Weak-beam strong-column mechanism Local story mechanism

Figure 3 Weak-beam strong-column mechanism

4.2 Limitation of weak-beam strong-column mechanism

When the survival of a structure under a severe earthquake motion is the design objective, the weak-beam strong-column design is probably most desirable. However, it should be noted that the weak-beam strong-column mechanism requires significant number of localities to be repaired after an earthquake. Especially, this is a problem in design where the required horizontal resistance is significantly reduced from the elastic response demand counting on ductile behavior. Yielding and associated damage may be developed at many localities even by a medium intensity earthquake motion resulting in significant repair cost after the earthquake for the continuing use.

On the other hand, the damage in the soft first-story structure was limited to the first story, and can be easily repaired using the state of construction technology as long as the first story does not collapse to the ground. Energy dissipation devices may be introduced to control the first-story deformation.

The capacity design method should not be limited to the weak-beam strong-column mechanism.

Story-sway mechanism as shown in Figure 2 should be avoided, but minor yielding of some columns in a story should be tolerated as long as the column should be able to support the gravity load.

4.3 Required Level of Horizontal Force Resistance

The required level of horizontal force resistance should be determined taking into consideration, (a) characteristics of the maximum intensity ground motion expected at the construction site, and (b) acceptable deformation at expected yield hinge regions of a structure. Design spectrum is formulated taking into account, (a) seismic risk, (b) soil condition at construction site, (c) building period, (d) approximate relation between the maximum response of linearly elastic and

nonlinear systems, and (e) structural irregularity. The acceptable deformation should be determined taking into account (a) the deformation capacity of members and (b) the function of a building. The required resistance may be dictated by the serviceability or repairability limit state. This is normally the case in the design of steel buildings.

4.4 Structural analysis

A linearly elastic analysis of a structure may be carried out using the gravity loads and lateral forces corresponding to the required resistance. A limited amount of beam end moments may be redistributed to adjacent beams as long as the equilibrium of forces is satisfied. The amount of flexural reinforcement should be determined at planned yield hinge zones to satisfy the required lateral resistance of the structure. The redistribution of design moments is necessary to develop optimal lateral resistance as required. However, large bending moment redistribution from a critical section may cause early yielding and hence excessive concentration of plastic deformation at the location.

A nonlinear analysis (commonly known as push-over analysis) under monotonically increasing lateral forces is carried out until the planned yield mechanism is formed in the structure or the acceptable damage is reached at one of critical regions. The lateral force distribution is taken similar to the first mode shape, but with additional forces near the top to consider higher mode contribution. The resistance at the yield mechanism formation should be greater than the required resistance. Excessive plastic deformation should not develop at limited localities.

4.5 Design of members not part of planned yield mechanism

In order to ensure the planned yield mechanism during an earthquake, extra resistance should be provided in the region where yielding is not desired and against undesired modes of failure such as shear failure and bond splitting failure along the longitudinal reinforcement. The action in members, not a part of the planned yield mechanism, may become much higher during an earthquake than those calculated by the pushover analysis by the following reasons:

(1) Horizontal force distribution during an earthquake can be significantly different from that assumed in the pushover analysis due to higher mode contribution,

(2) Actual material strength at the expected yield hinge can be higher than the nominal material strength used in design; therefore, the actions in non-yielding members may be larger at the formation of a yield mechanism with enhanced resistance at each yield hinge,

(3) Additional contribution of slab reinforcement to the bending resistance of a girder with deformation; i.e., the width of slabs effective to the flexural resistance of a yielding girder becomes wider with a widening of flexural cracks at the critical section,

(4) Bi-directional earthquake motion develops higher actions in non-yielding members than uni-directional earthquake motion normally assumed in a structural design, and

(5) Actual amount of reinforcement may be increased from the required amount for construction reasons.

The level of additional resistance must be determined by a series of response nonlinear analysis of typical buildings under credible earthquake motions.

CONCLUSIONS

This paper briefly reviews the development of earthquake resistant design of buildings. The state-of-the-art in seismic design is discussed with emphasis on the performance criteria of

buildings; i.e., (a) serviceability from frequent minor-intensity earthquake motions, (b) reparability from an infrequent but major-intensity earthquake motion, and (c) life safety from the maximum possible earthquake motion. With the introduction of performance-based engineering, the importance of reparability and serviceability criteria is emphasized.

The concept of capacity design is outlined. A weak-beam strong-column mechanism is selected as an example of the target yielding mechanism for design.

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