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Performance-based evaluation of reinforced concrete buildings in Turkish codes

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ABSTRACT: Turkish Seismic Code has been renewed in 2007 to include up-to-date requirements in structural design and earthquake engineering as well as in construction techniques. This new version of the code has detailed requirements related to the seismic evaluation and assessment of existing buildings by employing performance-based methods. Presently these methods are applied to existing buildings only, however it is expected that in a near future they will be modified and applied to buildings to be designed and constructed as well. Since 2007 numerous buildings have been analyzed and strengthened by using this code, some modifications seems to be necessary to reflect the experiences gained during these six years and to adopt the development in earthquake and structural engineering once more. Recently, another new code is prepared by the Ministry of Environment and Urban Planning to determine buildings having very low seismic safety, i.e., buildings having high risk of collapse or heavy damage, in other words “risky buildings”. The ministry intends to force pulling down these risky buildings for construction new buildings so that high life lost can be prevented in a significant earthquake. This new document uses performance-based principles, as it is employed in the Turkish Seismic Code for evaluation and assessment of seismic capacity of existing buildings. This paper aims to present a brief overview of the performance-based evaluation method in these documents comparatively.

1 INTRODUCTION

In severe earthquakes in Turkey, including the recent Erzincan (1992), Dinar (1995), Adana-Ceyhan (1998) earthquakes and the last Marmara (1999) earthquake, a large number of buildings was damaged. After these earthquakes numerous damaged buildings were inspected and found that most of them had inadequate seismic capacity. After this result, existing buildings also investigated in terms of their seismic capacity. Similar inadequacies also were found in them as well. Meanwhile the Turkish Seismic Code of 1975 modified completely and a new version published in 1998, where new developments in earthquake and structural engineering are reflected, such as, seismic load reduction factor, ductility and capacity design. After numerous heavy damaged buildings, publication of this new seismic code has been an important step towards design and construction of earthquake resistant buildings in Turkey. The new code contains detailed requirements for design of new buildings only. However, after each large earthquake there were numerous existing buildings to be checked and strengthened. The requirements of the code given for buildings to be designed were interpreted and used for the existing buildings as well. After numerous buildings were investigated and strengthened, it turned out that a more comprehensive requirement has been necessary to obtain more precise information on the seismic capacity of the existing buildings. After detailed work Turkish Seismic Code of 1998 a new chapter is added in 2007 to determine seismic capacity of existing buildings and various strengthening methods are presented. After six years of application, a modification is underway to include more up-to-date knowledge into the code and also to make the code more praxis oriented.

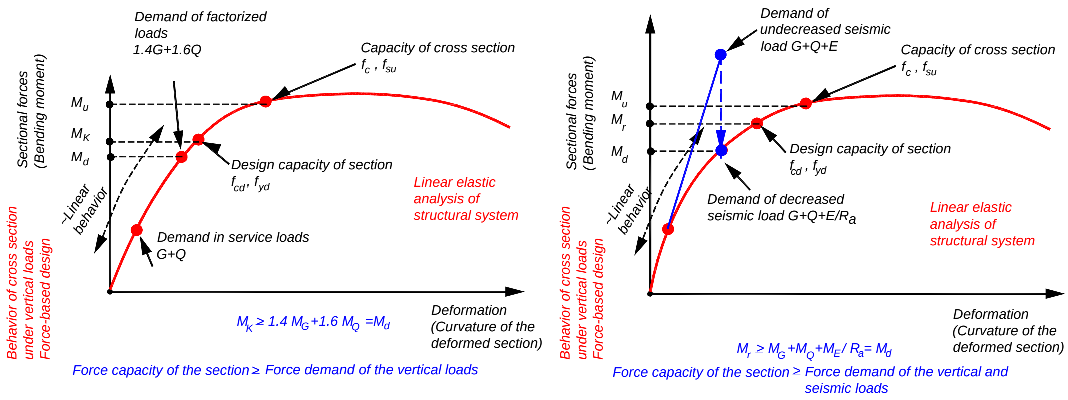

Figure 1. Design principle of a section subjected to death, live and earthquake loadings

On the other hand there is large number of buildings which have very low seismic capacity in Turkey. They were designed by following the requirements of the older seismic code which have very low seismic capacity. Even some of them had been built without receiving any structural engineering attention. These buildings are old and can not be strengthened easily due to architectural and financial considerations. Turkish government has started an extensive urban renewal program which provides several financial assistances to ensure a wide voluntary participation, such as, exemption from certain taxes. Ministry of Environment and Urban Planning is prepared a new guideline to identify risky buildings having very low seismic safety, in other words and high risk of collapse or heavy damage to force to owners pull down them and construct new ones, so that numerous life loss can be avoided in the expected Marmara earthquake. This guideline uses performance-based principles, as it is employed in the Turkish Seismic Code for evaluation and assessment of seismic capacity of existing buildings. Although the performance-based design methods display some modifications, they adopt the concepts of the related documents, such as, ATC40 (ATC 1996), FEMA 273 (FEMA 1997), FEMA 356 (ASCE 2000), FEMA 440 (FEMA 2005) and ASCE/SEI 41 (2007).

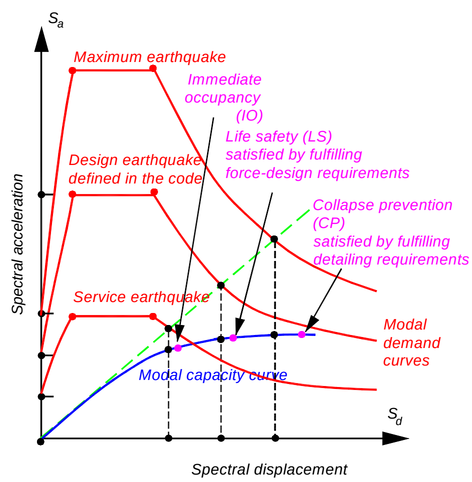

Figure 2. Performances implicitly stated in the Turkish Seismic Code

2 DESIGN OF REINFORCED CONCRETE STRUCTURES

Design of a cross section in the Turkish Seismic Code is carried out by considering the factored loads and the seismic load E in addition to the death G and the live Q loads as

$$M_{1.4G+1.6Q} \leq M_K$$

$$M_{G+Q} + M_E / R_a \leq M_K \qquad (1)$$

which is expressed for bending moment symbolically, however, can be generalized for all other cases as well. Here $M_{1.4G+1.6Q}$, M_{G+Q} and M_E are the bending moments due to the with and without factored death and live loads and due to the seismic loading of the elastic system, respectively, and M_K is the bending moment capacity of the cross section (*Figure 1*). The seismic load reduction factor is denoted as R_a which depends on the ductility level and on the redundancy of the structural system as well as on the acceptable damage level. As it is well known, use of confinement reinforcements at the potential hinge zones of beams, columns and shear walls increases the ductility, consequently the seismic load reduction factor, considerable, which are distinctly given in the code. Ductility enables designer to use of the capacity design principle as well. In fact has in background these force-based design requirements has the following performance objectives as well. When the structural system is designed to resist gravity and seismic loads, the code expects that the life safety performance is guaranteed. Furthermore when the additional structural details given in the code are fulfilled, the code expects that the collapse prevention is also assured under the maximum earthquake. The code also states that the structure should remain almost in elastic region or just above the elastic zone without much inelastic deformation, however no additional requirements is stated in the code. Probably it is expected implicitly (*Figure 2*).

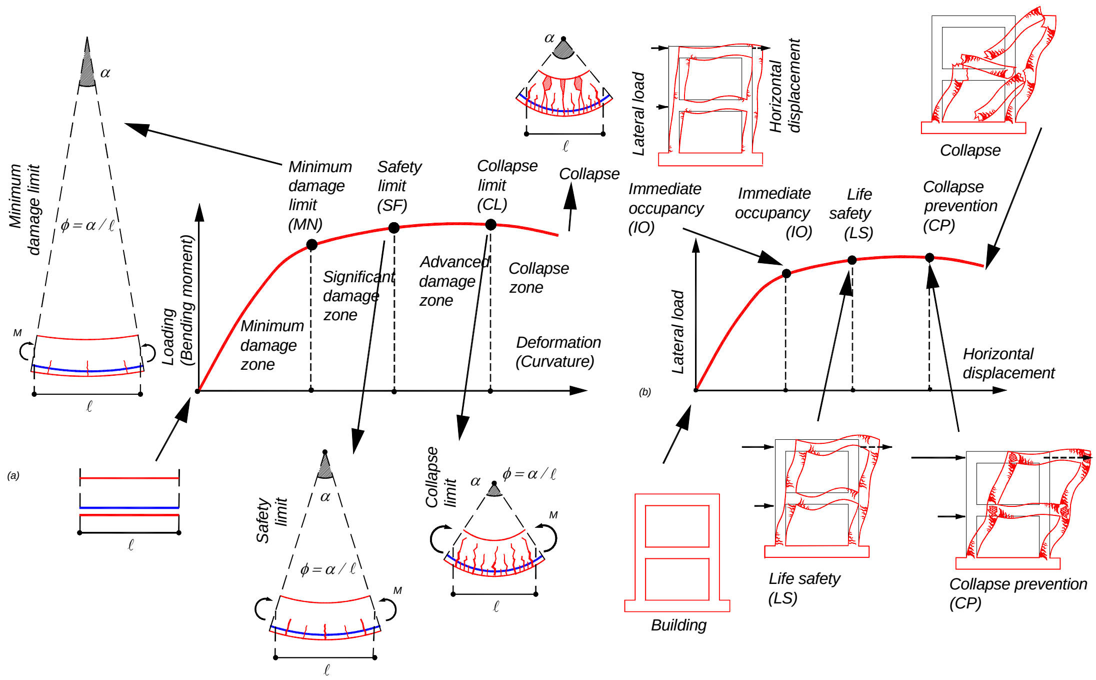

Figure 3. Force-deformation relationship a) for a cross section and b) for a building

3 PERFORMANCE BASED EVALUATION OF REINFORCED CONCRETE STRUCTURES

Behavior of a cross section subjected to certain loading and that of a building under an increasing lateral load representing seismic effect are shown *Figure 3a* and *Figure 3b*, respectively. In these figures the relationship between bending moment and curvature is displayed, which can be generalized for other type of loading as well. In the figures the damage zones of a cross section and the performance levels of a building are depicted quantitatively. The cross section and consequently the building display linear and elastic behavior, when the loading, deformations and displacements, are small. When the loading is increased, inelastic deformations appear and get larger as well. Due to inelastic deformation the lateral load capacity of the system increases, this increased capacity can be accepted under two conditions. The first one is that existence inelastic deformation capacity of the system, i.e., required ductility should be available in the sections and consequently in the structural system. For example, the bending behavior of a reinforced concrete section is ductile, whereas the shear behavior is brittle. The second one is that the inelastic deformations i.e., the controlled damage should be acceptable by the owner. For example, a specific level of damage can be acceptable in an apartment building, whereas it can not be acceptable in a school building. In the Turkish Seismic Code the numerical definition of the damage zones and that of the performance levels are defined separately for the two separate methods, i.e., the linear elastic evaluation and the nonlinear evaluation methods, which are summarized briefly in the following chapters. Performance-based seismic evaluation assumes that the performance of existing buildings can be defined and expressed by numbers and can be compared to the pre-defined performance limits which represents the acceptable performance levels. There are several key issues in this process to be assumed, such as, the uncertainty in gravity action and especially in seismic effects, the selection of the performance parameters to be evaluated in the structural analysis and employed in the comparison, and their digitization, such as numerical definition of life safety performance level and the others. However, all can be overcome by making suitable assumptions and using them until more suitable parameters can be defined.

3.1 Linear evaluation method

Equation (1) used for design can be employed to check the seismic capacity of existing buildings where the ductility can vary in very large range, when it is rewritten as

$$r = M_E \,/\, (M_K - M_{G+Q}) \leq r_{limit} \tag{2}$$

where R_a the seismic load reduction factor is replaced by r the demand-capacity ratio. R_a is a parameter to be assumed in the design by satisfying the related requirements given in the code, whereas r is a parameter to be evaluated and checked whether the structural element has the corresponding ductility by comparing to the corresponding limit.

The parameter r can be used to determine the damage region in which the structural elements are located, provided that the damage limit values r_{limit} are defined. In the code these limits are given for beams, columns and shear walls. As it is well known, ductility of beams increases as the tensile reinforcement decreases as the compressive reinforcement increases and as the shear force decreases. Furthermore, ductility increases, when confinement is present. The limiting values r_{limit} are closely related to ductility as it is given in the corresponding tables given in the Turkish Seismic Code. Ductility of columns depends on the same parameters as well, additionally normal force decreases ductility. Similar limits can be found for shear walls in the code as well. For evaluation of the parameter r for each structural element, a linear structural analysis is required which can be accomplished by using widespread common software which uses the regular elastic principles. Equivalent static load procedure (first mode approach) can be employed for low-rise regular buildings, i.e., for buildings which have more than eight stories and when the torsional irregularity is low. Otherwise modal superposition procedure should be adopted. Story drift ratio (δ_i / h_i) is also a measure of the deformability of each story and related to ductility, where δ_i and h_i correspond to the relative story displacement and to the story height, respectively. Consequently, the code gives limits for them as well, depending on the damage region.

3.2 Nonlinear evaluation method

Non linear analysis has two application procedures: nonlinear incremental equivalent static load procedure (pushover analysis) and nonlinear incremental dynamic procedure (nonlinear time domain analysis).

Pushover analysis is carried out regularly by adopting plastic hinge assumption to find the capacity of the system. The structural system is pushed by a lateral force, distribution of which represents the seismic loading, up to a specific displacement. This specific displacement is called the target displacement and represents the seismic demand. The code adopts the equivalent displacement principle which is modified for the structural systems having relatively large periods, as *Figure 4* shows. Having found the performance point, the inelastic deformations in the plastic hinges can be evaluated. Similarly the inelastic deformation of concrete and steel can be determined, which are accepted as a measure of damage. Their limits are given in The Turkish Seismic Code for various damage zones.

Nonlinear time domain analysis is direct integration of the equation of motions for a given set of ground motions. It is of prime importance to define the hysteresis rule for the plastic hinges, where the inelastic deformation expected and concentrated. Selection and scaling of ground motions which represent the demand is another delicate issue. At the end of the nonlinear analysis the plastic deformations found at the plastic hinge region should be compared to the corresponding limits, as it done in the pushover analysis.

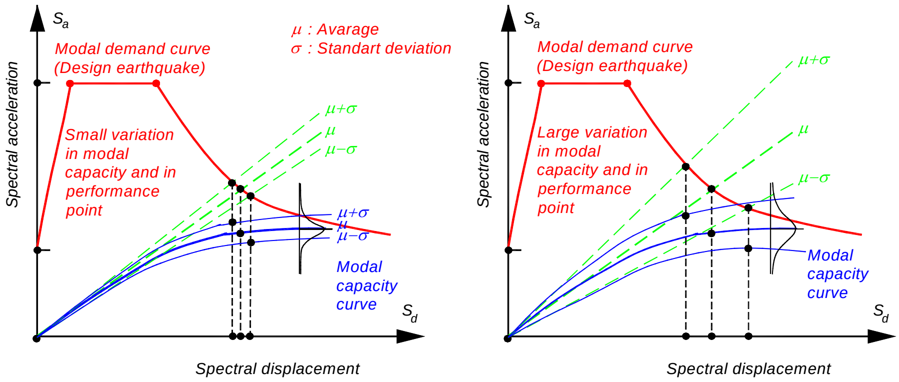

Figure 4. Variation of the modal capacity curve on the performance point

3.3 Performance evaluation

In the structural analysis the cracked (reduced) bending rigidity of cross sections are taken into account to obtain more realistic results. Damage zone of structural elements are determined from the damage zone of sections and it yields the damaged level of the story and that of the building. In the Turkish Seismic Code performance levels which have to satisfy by buildings are given, where most buildings have to satisfy two performance levels except residential buildings. However in design of new buildings only one design procedure is enough. Furthermore it is worth to mention that in various documents plastic hinge rotations are assumed as the main parameters which show the performance region of cross section. However, in the Turkish Seismic Code deformations of concrete and steel are adopted as the main parameters, which mean that the Turkish Seismic Code requires one more additional analysis step for decision on the performance.

4 RISKY BUILDING

Turkish government has started an extensive urban renewal program. For this purpose, Ministry of Environment and Urban Planning has published recently a guideline *Rules to determine risky buildings* (RDRB), to find buildings having high risk of collapse or heavy damage. This guideline uses performance-based principles, as it is employed in the Turkish Seismic Code. Risky building (can be located inside or outside of risky area) is a building that has completed its economic service life and carries a risk of severe damage or destruction which can be determined by using scientific and technical investigation. Risky area is an area which has risk of loss of life and property due to soil conditions and buildings on it. An area can be declared as Risky Area by the Council of Ministers upon the proposal of Directorate for Disaster and Emergency Management. Risky area has the following negative aspects:

- It has large number of risky buildings,
- It does not have adequate access roads,
- It is an area which chosen for application integrity,
- It has a soil having landslide and liquefaction potential,

The basic principles given in RDRB to determine risky buildings are:

a. They can be applied to residential buildings only,

b. Turkish Seismic Code requires that residential buildings are designed to satisfy Life Safety Performance Level under Design Earthquake. For this purpose, (a) corresponding seismic forces should be resisted by structural system (defined as a static force equivalent or defined in the corresponding spectrum) and (b) structural elements should satisfy details to increase ductility and to prevent the total collapse.

c. Performance level of risky buildings should be below Life Safety but above Collapse Prevention performance level. However, it should be closer to Collapse Prevention, so that building having very low level seismic safety can be found.

d. Rules of RDRB are more simple and easier to apply than those of the Seismic Code. Since RDRB does not give comprehensive rules, it can be apply for common low-rise buildings only, whereas other buildings will be referred to Seismic Code. In this way a kind of correspondence between the codes are provided.

e. Experiences obtained in application of the Seismic Code are reflected in RDRB.

Rules of RDRB are applicable for concrete having a height less than $25m$ and having not higher than eight stories above ground. Higher buildings are investigated by employing requirements of the Seismic Code and buildings which do not satisfy Collapse Prevention level are assumed to be risky. However, in this case, more concrete samples have to be taken and a more detailed examination will be necessary. RDRB considers mainly the critical story in seismic investigation. The critical story is the story which has less lateral stiffness with respect to the lower stories (*Figure 5a*). The critical story is not prevented laterally by soil. Since basements are surrounded by concrete or masonry walls, generally, the critical story is the ground story not the basement. However, there are exceptions as well. When there is a space between the basement and the soil surrounding it, i.e., when the basement is not surrounded by soil, then the critical story will be the basement.

4.1 Concrete and reinforcement

Evaluation of a building to determine whether it is a risky one starts to determine to reinforcement and concrete in the building only in the critical story. Amount and configuration of longitudinal reinforcement is checked in 20 % of columns and shear walls being minimum six. In the half of the columns and the shear walls it is done by removing concrete cover. The other half of them can be carried out by nondestructive methods. Spacing and diameter of lateral reinforcement are also determined in their middle and the confinement regions of columns. Tensile reinforcements at the support of beams are assumed what the analysis of the loading $1.4G + 1.6Q$ yields as defined in TS500. Compressive reinforcement at the support of beams is assumed as one third of the tensile reinforcement. For evaluation of quality of concrete, rebound hammer readings are carried out minimum in ten columns and shear walls. Concrete specimens are taken from five elements where minimum readings are obtained. When the critical story is larger than 400m^2, number of the concrete specimens is increased by one for each 80m^2. The existing concrete strength is assumed to be 85 % of the average strength, i.e. $f_{c\ existing} = 0.85\ f_{c\ average}$. New soil investigation can be carried out or results of the existing soil investigation can be used. When no information is available, local soil class can be assumed to be the most unfavorable soil class.

4.2 Performance evaluation

Figure 5b shows force-deformation relation for a reinforced concrete section, where damage regions and their limits are shown quantitatively, where performance limit of risky building is shown as well. As it is shown, this limit is between the Life safety and the Collapse prevention performance limits. First step of risk assessment of buildings is to obtain a structural layout and collect information related to structural system by considering the critical story. In order to consider uncertainty in determining the structural system and reinforcement, *the Knowledge Factor* is employed, which is 0.9 for very limited knowledge and 1.0 for comprehensive knowledge. Minimum knowledge factor will be used, when no original civil engineering drawings for the building are available. However, when they are available, comprehensible knowledge factor can be employed. The capacities of cross sections are reduced by using this factor. Structural model of the building is produced easily by replicating the critical story. Computer analysis of the building can be carried out easily by replicating the critical story. All these show that this procedure is simpler than that of Seismic Code. Structural system is obtained by replicating the critical story by considering the existing number of stories and balconies, and story heights. Analysis is carried out in two axes and in two directions by using the elastic (unreduced) spectrum. In the analysis the bending stiffnesses of beams and shear walls is assumed to be $0.30E_{io}$ and that of the columns $0.50E_{io}$ to represent effect of cracking, E_{io} is the gross bending stiffness of the section and $E_{cm} = 5000\sqrt{f_{cm}} \quad (MPa)$ is the modulus of elasticity. The analysis is carried out by employing *Linear Elastic Method* (*Equivalent Seismic Loading Method*) provided that building height above ground is lower than $25m$ and building has equal or less than eight stories and at most a moderate torsional irregularity, i.e. $\eta_b < 1.4$.

In Equivalent Seismic Loading Method, seismic lateral load is decreased with a parameter $\lambda = 1.0$ for two story above ground and $\lambda = 0.85$ for the other buildings) in order to take into account the difference between the actual mass and the modal mass of the system. In other case, the *Modal Superposition Method* is employed in order to take into account the contribution of the higher modes.

Contribution of the infill walls to lateral load resistance of building can be taken into account by multiplying the lateral load by 0.75 (25% reduction), provided that the following conditions are satisfied (*Figure 6*):

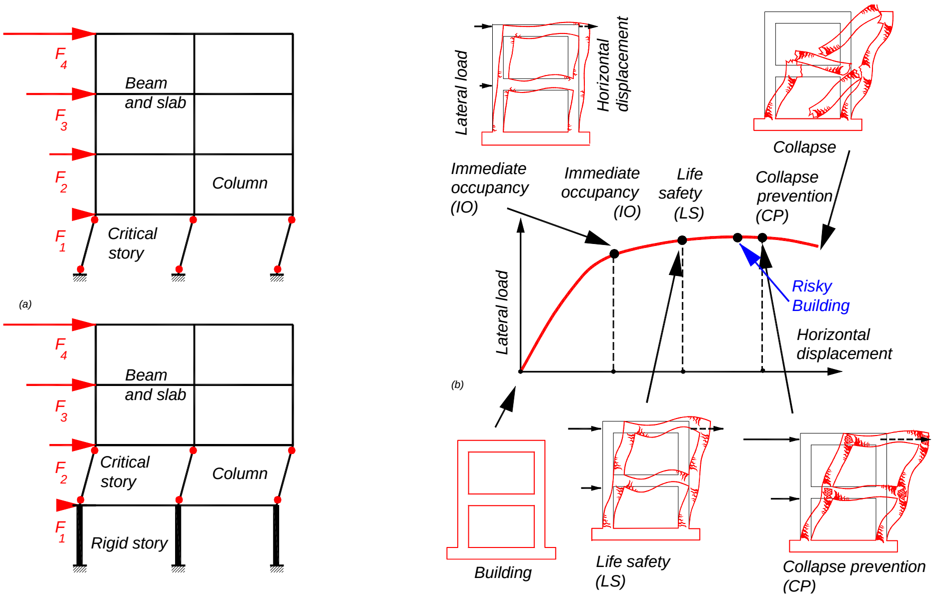

Figure 5. a) Definition of the critical building and b) force-deformation relationship for a cross section.

- Maximum story drift less than 0.015 [$(\delta / h) \leq 0.015$], in order to exclude cracked walls,
- Ratio of the area of the infill wall (excluding doors and windows opening) to the critical story area is less than 0.002 times number of stories above ground [$\Sigma A_{kn} / A_p > 0.002\ N$], in order to include solid walls only and to exclude the wall weakened by openings.

A partition wall can be included, when its door and window opening ratio less than 5% and when the ratio of its diagonal length to its thickness less than 40. In this way the slender partition walls are excluded, since they are very sensitive to out-of-plane deformations.

Columns are classified into three groups by taking into account their probable failure type depending V_e / V_r and lateral reinforcement detail in the confinement region, where V_e is the shear force demand and V_r is the corresponding capacity. In evaluation of V_r the corresponding normal force is obtained by using the loading [$G + n\,Q + E / 6$], where $4 < R_a = 6 < 8$ is assumed. Probable failure of A type column comes into being due to bending moment which is ductile. On the other hand probable failure of C type column is ductile and it is due to shear force. Columns of B types lay in between them. Similar definitions are done for shear walls as well and they are classified into two groups with respect to V_e / V_r and H_w / ℓ_w, where H_w and ℓ_w are its height and length, respectively. Shear wall is defined by its aspect ratio being larger than five [$b / h > 5$] to include the shear walls as defined in Seismic Codes of 1975 and 1998 as well. Probable failure of A type shear walls comes into being due to bending moment which is ductile and probable failure of B type shear walls is ductile and it is due to bending and shear force.

In the evolution of the structural system of the critical story, the demand/capacity ratio $m = M_{G+nQ+E} / M_K$ is an important parameter, which reflects damage level, where M_K is the existing capacity of the cross section and is obtained by using the loading [$G + n\,Q + E / 6$]. In the process, the demand/capacity ratio m and the story drift ratio δ are calculated and compared to the limiting values m_{limit} and $(\delta / h)_{\text{limit}}$:

$$m = M_{G+nQ+E} / M_K \le m_{\text{limit}} \qquad (\delta / h) \le (\delta / h)_{\text{limit}} \qquad (3)$$

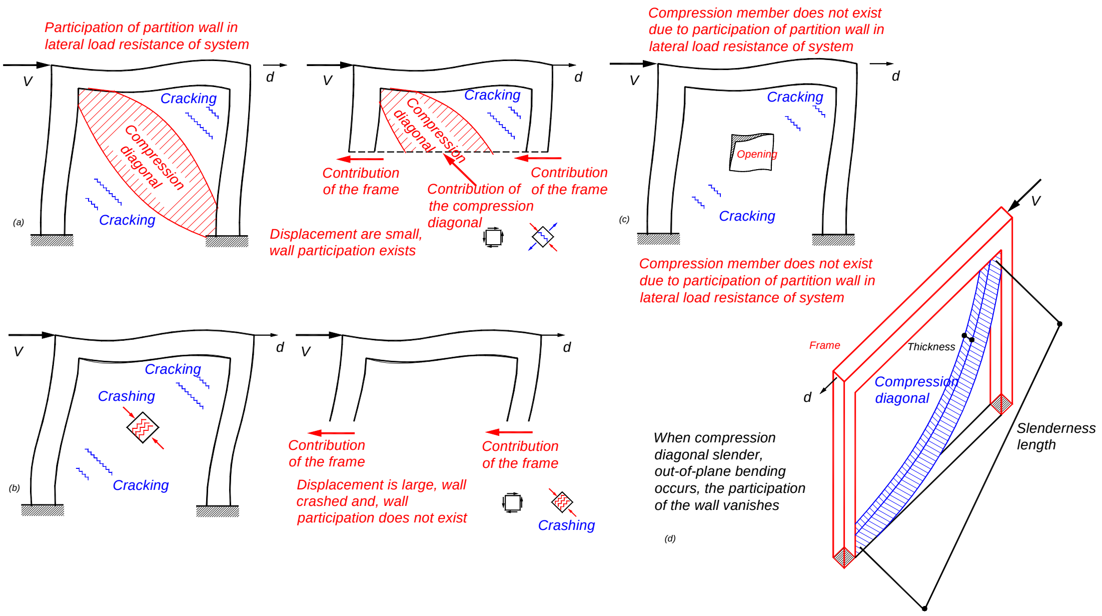

Figure 6. a) Participation of partition wall to the lateral load capacity of the infilled frame, b) opening in the infilled frame and c) out-of-plane deformation of an infilled frame.

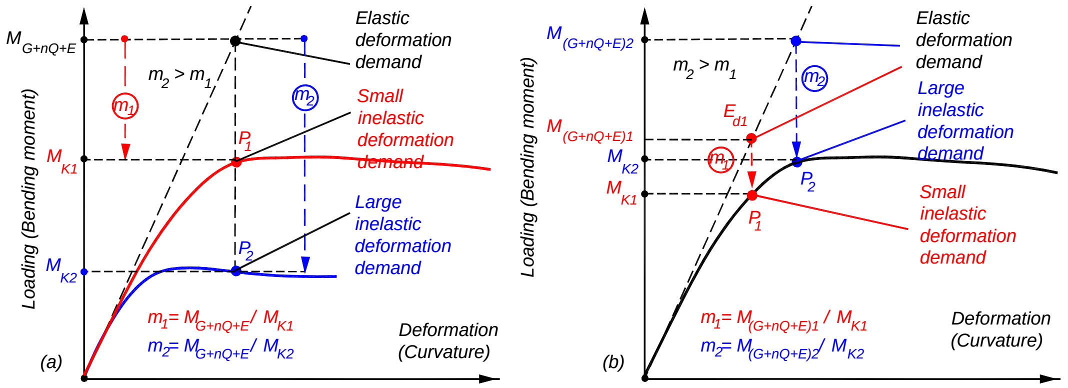

Figure 7. a) Deformation curves of two columns having different capacities subjected to the same earthquake loads and b) deformation curve of a column subjected to the same earthquake load.

When the drift ratio is less than 0.0075 and the ratio of the shear demand in the shear walls to the total shear demand α_S larger than 0.50, only comparison of the drift ratio is carried out. In RDRB m_{limit} and $(\delta / h)_{\text{limit}}$ are given, they depend mainly on the parameters which directly depend on ductility. *Figure 7a* shows the deformation curves of the column cross sections having different bending moment capacities subjected to the same earthquake. The performance points in two sections develop with different $m = Demand / Capacity$ ratios. As seen, larger m ratios correspond to larger inelastic deformation or to larger controlled damage for the column having lower capacity. When ductility of the column is small, then the corresponding limiting values should be lower. *Figure 7b* shows deformation curves of a column. For two different earthquakes, two $m = Demand / Capacity$ ratios are obtained. As seen, larger earthquake consequently larger m ratio corresponds to larger inelastic deformation or to larger controlled damage. In evaluation of V_e, capacity moments are needed, which can be obtained by using existing strength of concrete and steel can be used instead of strength moment obtained by using stress hardening in steel. When shear force obtained by employing $R_a = 2$ is smaller than V_e; this shear force can be employed instead of V_e. When the average compressive stress in shear walls and columns altogether under the loading $G + n\,Q$ larger than $0.65\,f_{cd}$, the building is assumed to be risky, when one of the columns or the shear walls goes beyond the risk limit. Depending on the average compressive stress in the columns and in the shear walls, the risk limit is given depending on shear force ratio. When the critical story is above the risk limit, the building is assumed to be risky. This shear force ratio is the ratio of the sum of the shear forces of the columns and the shear walls to the total shear force.

5 CONCLUSION

Performance-based seismic evaluation of existing buildings is adopted in Turkey specifically since 2007 by introducing it in the Turkish Seismic Code. However there are the documents prepared for design of high-rise buildings and for determining buildings having high risk in term of seismic loading. They employ the performance-based principles as well. All these show that performance-based requirements will be used more extensively in the near future in Turkey. Performance-based analysis generally preferred to gain more insight into structural behavior and to obtain seismic capacity of existing buildings more accurately. However, there are drawbacks as well, which originates from the same detailed analysis.

Turkish Seismic Code defines “Immediate occupancy”, “Life safety” and “Collapse prevention” for seismic safety level of a building. Performance level of risky building is defined in between “Life safety” and “Collapse prevention” and the corresponding analysis level is defined simpler than the analysis given in the Seismic Code. Analysis of selected buildings confirms this expectation that the rules to determine risky buildings gives the minimum requirements, if desired; more detailed analysis can be carried out as well. RDRB bases on structural system of the critical story; the model of the building is produced by replicating the structural system. RDRB can be used for a large number of buildings in the building stock. When a building is higher than eight stories often the geometry of the column and their reinforcement display significant variation between stories, therefore the requirements of Seismic Code is employed. The limiting values of m and δ / h is determined by considering recent studies.

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