SEISMIC DAMAGE AND FRAGILITY OF RC BUILDINGS

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Abstract: *Seismic actions cannot be predicted in time, location or intensity. Serious earthquake actions can cause the occurrence of different levels of damage of the elements and the structure as a whole, which can even lead to their collapse. The methods for evaluation of seismic performance of structures are discussed in this paper and the focus of the paper is on reinforced concrete (RC) buildings. Building structures are designed and built according to different standards that were valid at the time of their construction. Those standards were, more or less, less demanding than the current European, American and other modern standards. Criteria for the determination of damage degree are discussed in the paper. Review and comparison of international Code provisions related to this topic are discussed as well.*
Fragility analysis of existing buildings with different structural systems is a rational approach, based on the application of probabilistic methods. They are applied in order to determine and predict the structural performance and probable levels of damage. The classification of damage level and residual bearing capacity is essential after strong earthquake. This is necessary in order to decide the appropriate interventions, such as shoring and others. They are evaluated based on the condition of structures, considering: residual deformations, cracks, crush of concrete and so on. The methods of nonlinear analyses are used in order to determine the structural response and the results of the analysis are used for the fragility assessment. Post-earthquake assessment and analysis of seismic performance are analysed.

Key words: *Earthquake actions, seismic damage assessment, reinforced concrete buildings, residual seismic capacity, post-earthquake evaluation*

1. Introduction

The structures have to be safe both for static as well for seismic actions and provide adequate capacity and acceptable deformation, according to the recommendations given in the current Code. Many reinforced concrete (RC) buildings have either collapsed or sustained different levels of damage during past strong earthquakes. European codes EN 1998-1 [1] and

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1998-3 [2] provide the rules for seismic design of new and existing damaged structures, respectively. Federal emergency management agency (FEMA) [3] and applied technological council (ATC) [4] work very actively in assessing conditions of structures after seismic events and for its upgrading. Contemporary seismic design of structures is mainly based on the assumption of the ductile response and yielding probability of some parts of the structure, without formation of the structure into a mechanism of brittle failure.

The terms used are adapted to serve the purpose of this paper, and briefly explained (more in *fib* Model Code 2010) [5]. "Damage" is any adverse consequence for the physical state of a structure or structural component caused by earthquake. "Assessment" comprises the process of gathering and evaluating information about the form and current condition of a structure or its components [6].

Concrete structures of buildings comprise following structural types: concrete moment frame, concrete shear wall buildings, dual system - frame with shear walls, and concrete frame with infill masonry shear walls, precast concrete shear wall buildings, precast concrete frame [1], [3]. RC buildings may be with stiff (preferable) or/and flexible diaphragms floor structures (concrete slabs/beams or flat slabs). Lateral forces are resisted by concrete moment resistance frames that develop their stiffness through monolithic beam-column connections. Foundations consist of concrete spread footings or pile foundations. In concrete frame with infill masonry seismic performance depends on the interaction between the frame and infill panels [7].

2. Damage of concrete structural elements

During the assessment of the earthquake induced damage, the following must be considered:

- soil properties and seismicity of the region;
- ground motion characteristics and response spectra for the earthquake (peak ground acceleration);
- type of structures.

Analysis of earthquake-induced damage indicates that ground effects are a serious contributor to damage of the built environment [8]. Many structures suffered damage because of soil liquefaction or landslides. Classification, description and photograph documentation of the damage contributes to the assessment of the usability of damaged buildings and selection of the adequate repair procedures. In [9] the classification of damage to structures and their respective causes in Montenegro on 15th April, 1979 was presented. Wide classification of concrete structures and mechanisms of failure was discussed in [10]. Data relevant to classification can be classified into following groups:

- Identification parameters;
- Structural and quality parameters;
- Damage and usability parameters.

Description of the damage caused in different countries by the earthquakes are published in the special issue or paper in Journal and Proceedings, i.e. in Turkey [11], USA and Japan [12], Chile [13], Montenegro [9], NZ [14], and different location and aspect [15]. Damage of foundations is considered in [16], [17], [18]. Earthquake damage can be evaluated best shortly after the event happened; when emergency operations are still in progress, using [4], [19], [20]. The structures which have been built under modern earthquake resistance codes show better behaviour and response than the structures built according to the older codes.

Errors in the structural concept (wrong choice of structural type) of the building lead to the worst cause of damage. System aspects related to: lack of strength and deformation capacity; vertical irregularity; horizontal irregularity; inadequate diaphragms; interaction with non-structural elements; previous modifications and damage; pounding of adjacent buildings; pancake failure; inadequate stiffness and result in damage to non-structural elements and foundation inadequacies. In precast concrete structures, the most frequent causes of damage are: inadequate diaphragm action; poor joint and connection details, inadequate connections between structures and non-structural elements and improper design and detailing of ductile elements [7].

3. Assessment condition of structure

Before structural redesign for design earthquake, it is very important to set a criterion for the evaluation of seismic safety of existing RC buildings. During the assessment of the current seismicity of the region, characteristics of the measured ground motions, seismic load demands (including earthquake spectra) and damage mechanisms need to be investigated. In high-seismicity area, rehabilitated buildings need to provide ductile instead of the brittle behaviour and convenient mechanism for the structural behaviour and response. When this approach is implemented in the design of frame structural system buildings, the damage is likely to occur at first in beams and then in columns. The columns in frame need to be stronger than beams, and foundations should be stronger than columns. Members must be detailed properly in order to have large ductility and so that the building as a whole can deform considerably despite seismic energy. Further, connections between beams and columns and columns and foundations should not fail, so that beams can safely transfer the forces to columns and columns to foundations. It is very important to provide the rigid diaphragm action - floor slabs should be stiff in its own plane.

Structural conditions assessment after seismic events includes: global strength, global stiffness, and configuration (regularity) for different structural system. The lack of global strength is caused by insufficient frame strength, resulting in excessive demands on the existing frames. Yielding or fracturing of the beams, columns, and/or joints and connections could lead to excessive drifts. As a result, the building could be deemed irreparable after an event. This is likely to cause structural damage to the connections and non-structural damage to the partitions and cladding [3]. Soft story conditions occur when stiffness from one floor to the next changes abruptly. This is common at ground floors of commercial and office buildings with tall first stories. It could also occur at mid-heights of five-story to fifteen-story buildings that have not been designed for higher mode effects and near field motions. It is very important to provide continuity of structural elements.

The structural engineer (SE) has to estimate in every case the residual strength, ductility and stiffness of the structure, and decide whether or not they are sufficient to allow the use of the building at an acceptable level of risk. This evaluation, based on the existing evidence, is probably the most difficult problem for SE, much more difficult than the design of a new building. Extensive calculations are needed, using the information collected from site observation, in order to determine the residual strength, stiffness and ductility of the structure. In order to estimate the residual strength, stiffness and ductility of a structure, the SE has to trace the damage in the structural system and non-structural elements. Crushing of concrete at the top or the bottom of a column accompanied by buckling of the longitudinal reinforcement, X shaped cracks in shear walls with significant axial loading and in short columns are some of damage examples [7], [16].

4. Analysis of earthquake resistant structures

The design philosophy of earthquake resisting structures may be summarized as follows:

- under *minor* but frequent shaking - the main members of structure should not be damaged;

- under *moderate* but occasional shaking - the main members may sustain repairable damage; and;
- under *strong* but rare shaking - the main members may sustain severe (even irreparable) damage, but the building should not collapse.

After minor shaking, the building will be fully operational within a short time and the repair costs will be small. After moderate shaking, the building will be operational once the repair and strengthening of the damaged main members is completed. But, after a strong earthquake, the building may become dysfunctional for further use, but will stand so that people can be evacuated. Some important Hospitals and fire stations play a critical role in post-earthquake activities and must remain functional immediately after the earthquake [20].

Risk assessment is affected by a large uncertainty, depending on hazard, structural and damage analysis. Possible criteria for the mitigation of seismic risk and some of the alternative choices that may be adopted for strengthening, with reference to: a) modification of damage and collapse modes strengthening individual elements or locally increasing the deformation capacity; b) inspection of additional systems resisting horizontal actions; c) introducing of base isolation, with the objective of capacity-protecting the existing structure; d) reduction of displacement demand by added damping or introducing tuned mass system [21]. Case c) and d) not considered in this work [7].

In the recent 7.8 magnitude earthquake that had severe consequence on the infrastructure and population in Turkey and Syria, more than 50000 lives were lost. Nearly 2.2 million people were relocated [22].

There are two possible reasons which affected the collapse of the buildings during the earthquake:

- the buildings were not designed with earthquake-resistant foundations;
- the newer buildings were designed with earthquake-resistant foundations but were not built in accordance with such design [23].

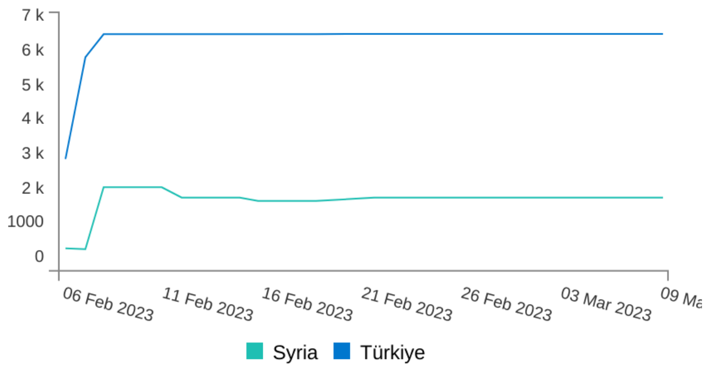

Figure 1. Number of Buildings Destroyed, after [24]

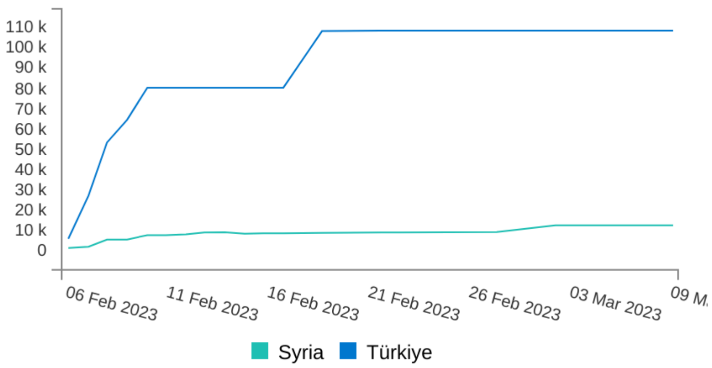

Figure 2. Number of People Injured, after [24]

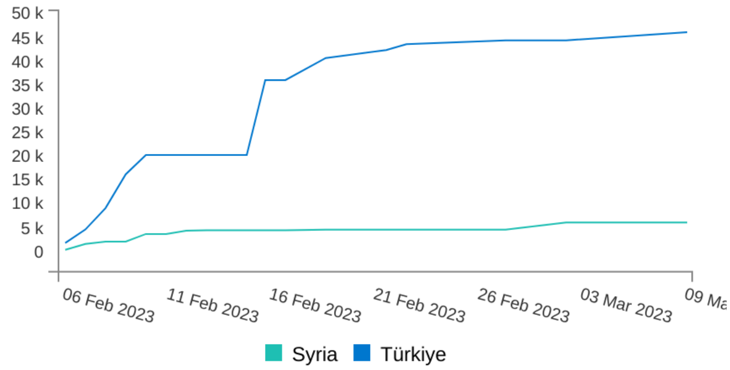

Figure 3. Number of People Killed, after [24]

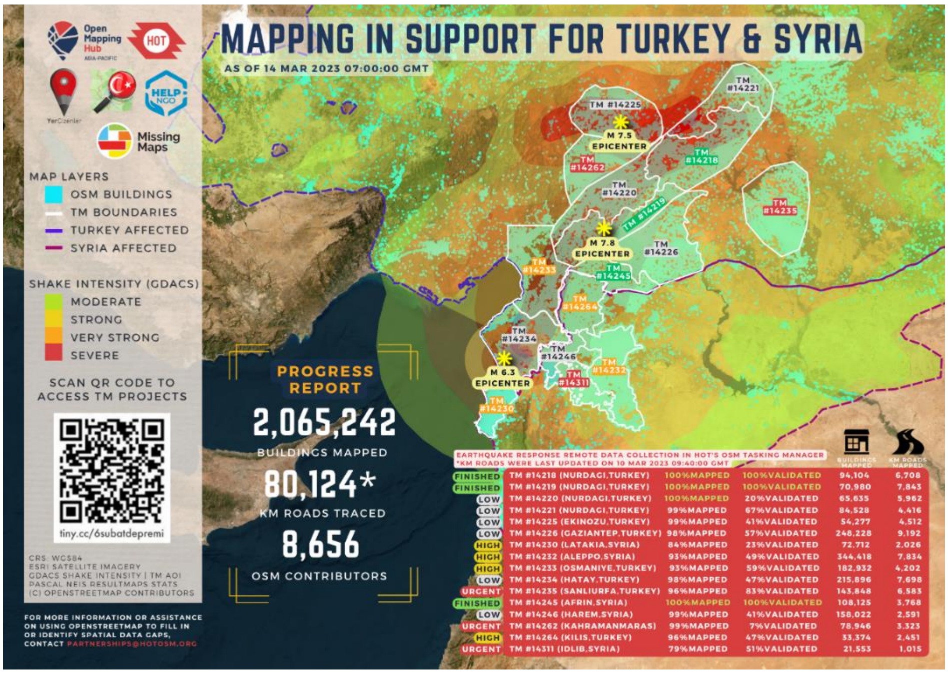

Figure 4. Summary of HOT Tasking Manager Mapping in Support of Turkey & Syria on 14 March 2023, after [25]

The evidence for past earthquakes of magnitude 9.0 suggests that they recur on average every 500 years, but the actual intervals between events are far from predictable—such earthquakes have been separated by as many as 1,000 years and as few as 200. The estimates of the sizes of pre-1700 earthquakes are also uncertain.

No one can predict the exact date of the next strong earthquake, but it is possible to anticipate the likely impacts on the region's communities, infrastructure, and economy. Due to the number of variables, earthquake simulations do not provide precise forecasts of every effect in every location, but they can provide useful insights. The results may help individuals, organizations, businesses, and communities define their risks, pinpoint their chief vulnerabilities, and make informed decisions as they develop emergency and continuity plans and invest in seismic mitigation strategies. The earthquake itself cannot be averted, but, with awareness and planning, many of the damaging impacts can.

Aftershocks that follow the main shock can bring down already weakened buildings. While the size and frequency of aftershocks will diminish over time, a few may cause additional damage long after the initial quake. This occurred in New Zealand, where the magnitude 7.0 Darfield earthquake in September of 2010 was followed over five months later by a magnitude 6.1 aftershock, which caused far more damage to the city of Christchurch than the main shock.

Building's performance during the earthquake depends on when it was built, where it is located, what it is made of, and how long the ground shakes. For tall buildings, large-magnitude earthquakes pose a particular challenge: High-rises and other tall structures vibrate at a lower frequency than shorter buildings. Because the frequency of a large earthquake's seismic waves is also low, some tall structures may resonate with the waves. This will amplify the intensity of the shaking and may increase the damage. Some buildings should hold up fairly well. Structures that were designed and built to meet current seismic codes may sustain damage, but should not collapse and may be usable after the earthquake, although they may lack utilities [26].

According to [27], in the Damage Evaluation Guideline (JBDPA 2015), the state of damage of each structural member is first classified into one of the five classes shown in Figure 5.

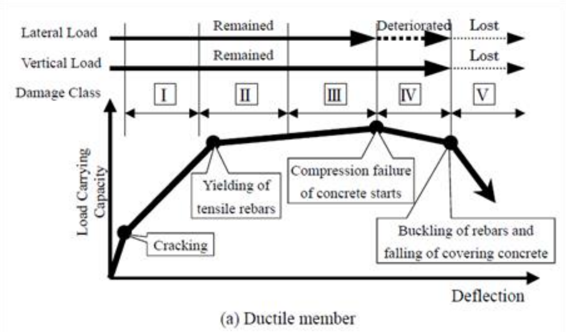

Figure 5. Idealized lateral force-displacement relationships and damage class (JBDPA 2015), after [27]

Examples of damage classes III (X shape cracks with a width of about 2mm on structural concrete), IV (exposed rebars without buckling or fracture) and V (buckling and fracture of reinforcing bars and crush of core concrete) are shown in Figure 6.

Figure 6. Damage class: III (left), IV (middle) and V (right), after [27]

Figure 7 (left) shows typical collapse mechanism of frame structures. As was revealed in past damaging earthquakes in Japan, typical life-threatening damage is generally found in vertical members, and story collapse mechanism, as shown in Figure 7 (right), is formed.

Figure 7. Story collapse of reinforced concrete buildings due to past earthquakes: 1978 Miyagi-ken-oki Earthquake (left), 1995 Kobe Earthquake (right), after [27]

Many building collapses during earthquakes may be attributed to the fact that the bracing elements, e.g. walls, which are available in the upper floors, are omitted in the ground floor and substituted by columns. Thus, a ground floor that is soft in the horizontal direction is developed (soft storey). Often the columns are damaged by the cyclic displacements between the moving soil and the upper part of the building. The plastic hinges at the top and bottom end of the columns lead to a dangerous sway mechanism (storey mechanism) with a large concentration of the plastic deformations at the column ends. A collapse is often inevitable (Figure 8). The infill of parapet walls into a frame structure without the addition of joints can cause short column phenomena. Shear failure occurs, or – in cases of sufficient shear strength – a sway mechanism develops with possibly significant second order effects (*P-Δ* effect) (Figure 8) [29].

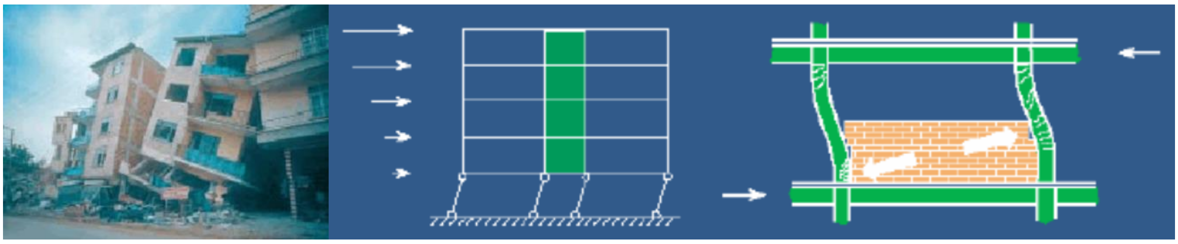

Figure 8. Sway mechanisms - soft storey ground floors (Izmit, Turkey 1999), soft-storey ground floors, partially infilled frames, after [28]

Since 1981, an excessively flexible story, compared with the other stories in a building, has been restrained or has been required to have extra strength. This was realized by the introduction of the stiffness ratio. In addition, the detailing of transverse reinforcement has been improved. However, several buildings that conform to the current design code requirements collapsed in the open first story (Figure 9, left). The collapse calls attention not only to a uniform distribution of story stiffness along the height of buildings but also to an excessively weak story, compared to the other stories, even if it has greater story shear strength than that specified by the code.

Numerous columns and walls were observed to fail in shear. Such failures were pointed out in past earthquakes. This kind of damage can be attributed to short columns, insufficient shear reinforcement, no cross-tie or supplemental ties, and inadequate construction (Figure 9, right).

Figure 9. Shear failure of a column due to inadequate transverse reinforcement, after [28]

A conspicuous mode of failure of reinforced concrete buildings in the earthquake is the story collapse at a mid-height story (Figure 10). Several reasons described below are potentially responsible for these collapses:

- Unless a building structure is designed so that a certain collapse mechanism is intentionally formed, damage may concentrate in any story.
- Damage can concentrate at a story in which the story shear strength and/or stiffness changes abruptly between adjacent stories. Several buildings were found collapsed at the story where the structural system changed from steel-encased reinforced concrete (SRC) to reinforced concrete. In another case, the number of structural walls in the collapsed story was found to be much less than the other stories.
- The seismic design load distribution over the height used in the old design codes is different from current codes. Although the codes cannot be compared directly due to differences between the design procedures, the proportion of design story shear was smaller at the middle stories in the old codes than the current ones.
- Large vertical accelerations may have generated large compressive and tensile axial loads in the columns, which resulted in ductility and shear strength reductions. The interaction of horizontal and vertical acceleration may also be a reason.

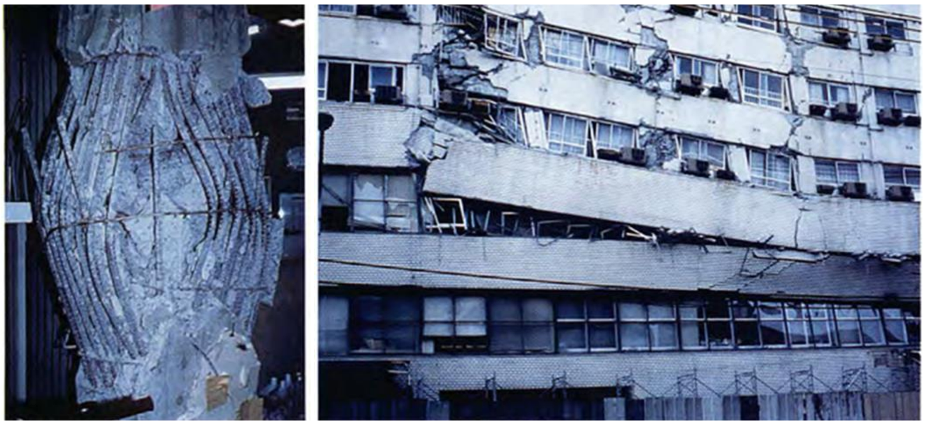

Figure 10. A post-1981 apartment building that collapsed at the soft first story (left) and shear failure of wall (right); An apartment building that collapsed at the third story due to torsion resulting from eccentricities of stiffness and mass (left), after [29]

Figure 11. Collapse associated with beam-column joint failure, 1994 Northridge earthquake (left); *Foundation failure:* Inadequate foundation conditions, including ground failure, ground settlement (right), after [30]

After the damage experienced by existing reinforced concrete (RC) buildings during significant earthquakes in recent decades, performance-based earthquake engineering methodology (PBEE) has been proposed to evaluate the seismic performance of RC multi-story buildings. PBEE is a framework that leads to a system's required seismic performance at different earthquake intensity levels. The importance of utilizing PBEE is that the degree of damage, losses, and structural repair costs may be anticipated when a building is subjected to an earthquake. It must be noted that even if buildings constructed according to traditional design philosophy meet with the existing earthquake regulations, the damage, losses, and expenditures associated with an earthquake do not generally correlate to that [31].

System performance levels are divided into four main categories: fully operational (Serviceability), operational (Damage Control), life safety (Life Safety), and near collapse (Collapse Prediction), and hazard levels are divided into four main events: frequent, occasional, rare, and very rare event. The Pacific Earthquake Engineering Research Centre (PEER) established PBEE to account for uncertainties in earthquake intensity, response of structures, damages, and losses [32], [33]. The other important aspect of utilizing PBEE is that it can estimate the seismic performance of both new and existing RC structures. PEER-PBED framework, shown in Figure 12 below, comprises of four stages of analyses: hazard, structural, damage, and loss analysis, and the uncertainties associated to each stage are explored below [34].

As a result, the performance of the lateral force resisting components must be evaluated to determine the seismic performance of reinforced concrete (RC) buildings subjected to seismic loading. RC columns are usually used as the lateral force resisting components. The performance of RC columns has been investigated using the framework of the PEER-PBEE. This is because PBEE can be used to predict damages, losses, and repair costs depending on the earthquake intensity. PEER-PBED framework: [34]

- Hazard Analysis;
- Structural Response Analysis;
- Damage Analysis;
- Loss Analysis.

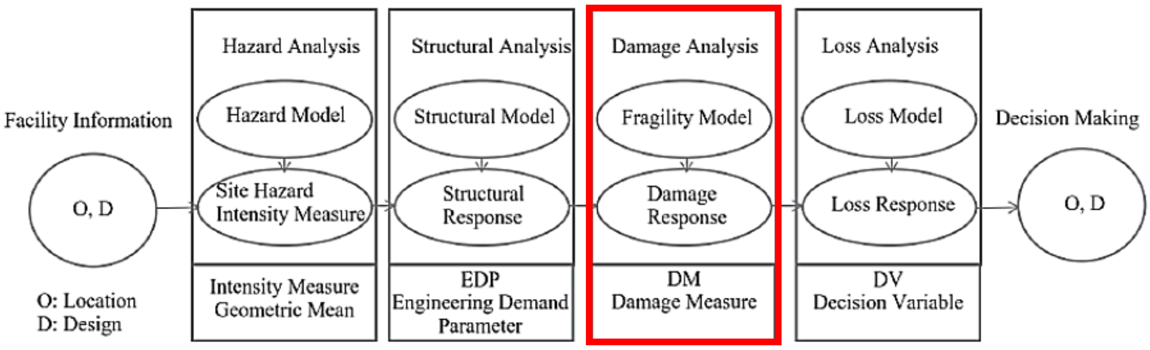

Figure 12. PEER-PBEE methodology, after [34]

5. Calculation of damage index and fragility curves

The short review of fragility assessment was done in paper [35], using damage index (DI), according to [36]. According to [37], one can define a fragility function as a mathematical function that expresses the probability that some undesirable event occurs as a function of some measure of environmental excitation. Fragility function represents the cumulative distribution function of the capacity of an asset to resist an undesirable limit state.

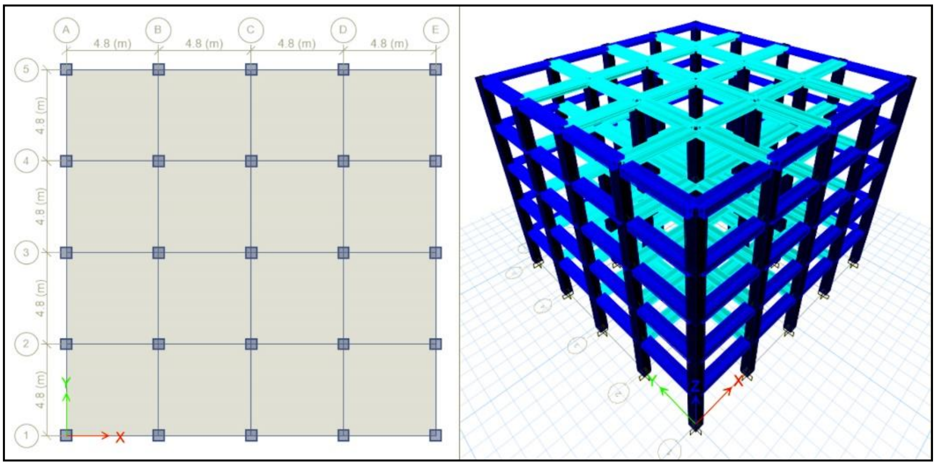

Figure 13. a) Building plan; b) Numerical model, after [35]

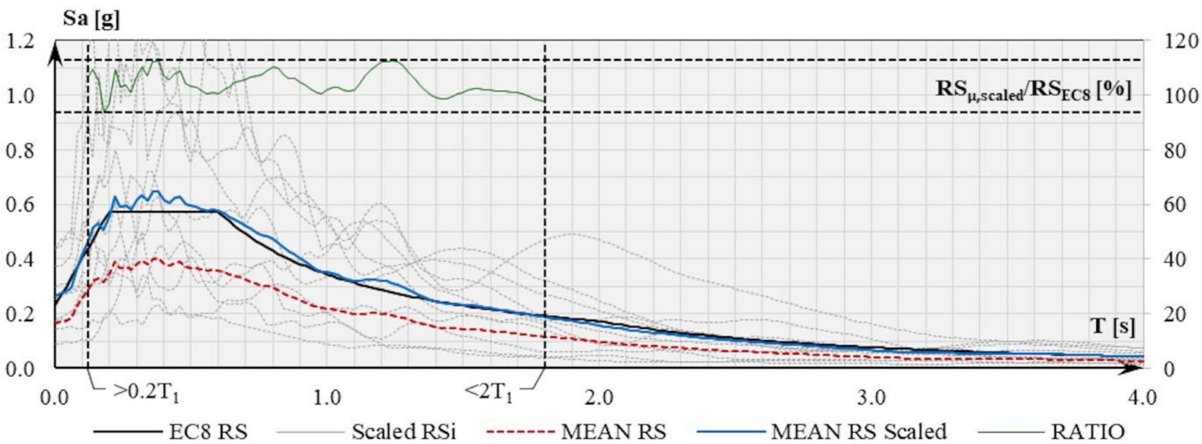

Figure 14. Response spectrums from the analysis (scaled RS_i, mean RS and mean scaled RS), after [35]

The subject of the analysis is office-residential building (Figure 13) with 5 levels (ground floor+4 stories). The structural system exhibits the properties of a frame structural system [1]. The length of one span in both directions is 4.8 m which makes the total length of the building 19.2 m in both directions. The height of the first story is 3.6 m and the height of the other stories is 3.2 m which makes the total height of the building 16.4 m. All vertical elements are fixed at the bottom level of the structure.

The design of the structure as ductility class high (*DCH*) system is done according to the recommendations given in the set of structural Eurocodes [1], [38], [39], [40]. Material properties of concrete *C35/45* and reinforcing steel class *C* (f_{yk} = 500 MPa, E_y=200 GPa) have been adopted. The calculations are performed using [41].

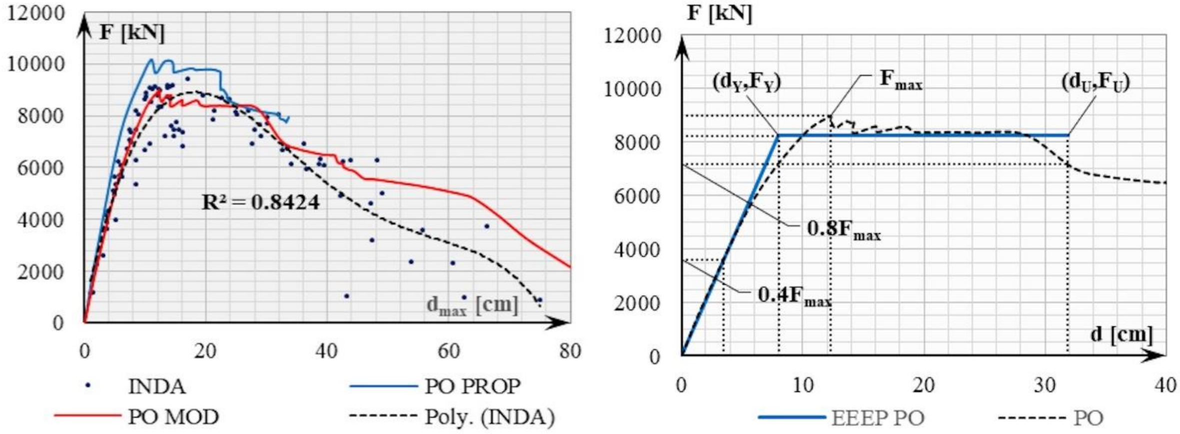

Figure 15. *NSA* and *INDA* results (left) and pushover curve bilinear approximation (right), after [35]

The results of *NSA* for mass-proportional and modal load distributions and *NDA* are shown in Fig. 15. To perform the calculation of DI_{PA}, it was necessary to do an bilinear approximation of *NSA* pushover curve, using Equivalent Energy Elastic-Plastic (*EEEP*) method and determine yielding (d_Y,F_Y) and ultimate capacity (d_U,F_U) points.

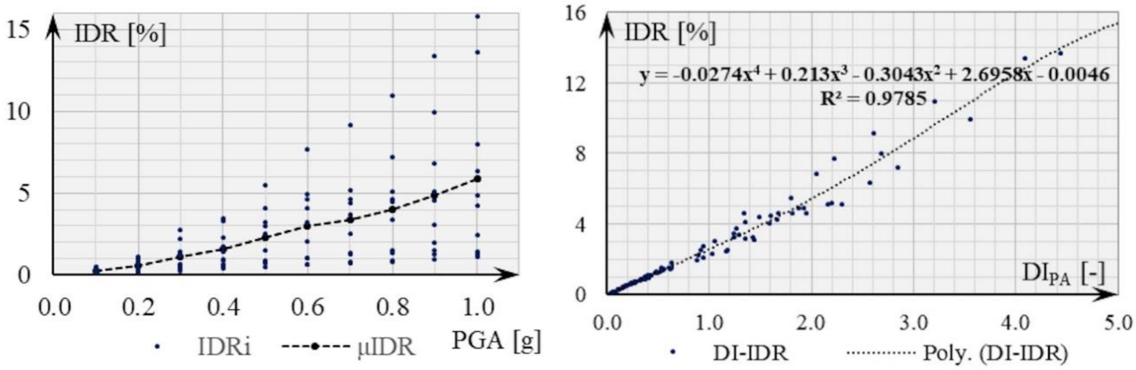

Figure 16. *IDR* results (left) and relationship between DI_{PA} – *IDR* (right) obtained using *NDA*, after [35]

Damage of a structural system may be quantified through threshold performance points, which represent the values of *EDP*, which are obtained by *NSA* and *NDA*. There are several methods to define damage state performance points. *Park* and *Ang* methods to define damage state performance points and calculate damage index [36] for structural damage (DI_{PA}) is calculated according to following equation:

$$(1) \qquad DI_{PA} = \frac{d_M}{d_U} + \beta \cdot \frac{1}{Q_Y \cdot d_U} \cdot \int dE$$

where d_M represents maximum deformation under earthquake in *THA*, d_U ultimate deformation capacity under monotonic loading; Q_Y yield strength under monotonic loading;

dE incremental absorbed hysteretic energy during the earthquake and β is non-negative parameter representing the effect of cyclic loading on structural damage, usually equal to 0.15 for RC structures [42].

In case of the calculation of fragility curves, using *EDP* as a referent values, the probability of the occurrence of a defined damage state at a particular intensity measure value $\left(P_{DS_i|IM_j}\right)$ can be calculated using the expression:

$$(2)\qquad P_{DS_i|IM_j}\left(\mu_{LN,IM_j}^{EDP_i},\sigma_{LN|IM_j}^{EDP_i}\right)=1-\Phi\left(\frac{ln\,EDP_i-\mu_{LN,IM_j}^{EDP_i}}{\sigma_{LN|IM_j}^{EDP_i}}\right)$$

where $\mu_{LN,IM_j}^{EDP_i}$ and $\sigma_{LN|IM_j}^{EDP_i}$ are mean and standard deviation in *l.l.s.* of *PDF* of the variable $\ln EDP$ for a particular $\ln IM_j$ value. $\ln EDP_i$ is the lognormal value of a *DS* threshold. Probability values are calculated at each IM_j, for each DS_i. When all the probability values are calculated, the set of obtained points is fitted for each *DS*, by using maximum likelihood estimation (*MLE*) method [37].

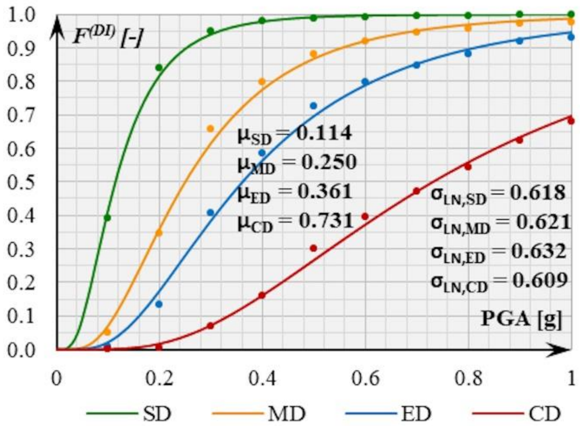

Figure 17. Fragility curves calculated according to *Park* and *Ang* [36] *DS* thresholds, after [35]

6. Conclusions

This paper provides an overview of the literature on the behaviour of RC elements and buildings. Damage affects the behaviour of individual components differently. Some exhibit ductile modes of post-elastic behaviour, maintaining strength even with large displacements (desirable). Others are brittle and lose strength abruptly after small inelastic displacements (undesirable) [43]. The challenge is to identify acceptable forms of damage and desirable building behaviour during earthquakes [44].

Seismic evaluation of the existing structures is a complex task. Use of sophisticated evaluation and strengthening procedure is reasonable when the level of knowledge for the structural system is relatively high. Use of advanced technology materials is only recommended, when concrete quality the existing buildings is relatively good [44].

In decision process for the degree and the type of intervention, the following factors are considered: the layout of structural system; the strength of structures; the flexibility of structures and the ductility. The ductility requirements for RC buildings are: strong columns-weak beams; adequate shear reinforcement so that bending mode of failure is provided; confined compression zones with close hoops or ties [1], [44].

Classifications are the best from the aspect of structural usability problems, Damage classifications are related to structural usability classification. It is described in FEMA [3].

These classifications are a good basis for taking urgent measures to support horizontal load-bearing elements and to secure parts of the structure from partial or complete collapse. Unstable parts of the structure that are damaged and pose a threat to the stability of the structure must be removed in a planned manner. Detailed classifications are the basis for repairs and strengthening of structures.

In this paper, an overview of possible damage in RC buildings during the seismic action is presented. Their cause and consequences have also been introduced. Damage indices are such as damage index (DI) [36] considered an effective tool to quantify the degree of structural components' damage or the overall structural damage. Damage indices can be used to evaluate the damage induced due to seismic actions. Researchers are widely using the well-known Park-Ang damage index (DI) [36] to assess the damage level analytically because of its high accuracy and simplicity in application [45]. Numerical example of the calculation of damage index and fragility curves as an overview from the research paper [35] of the authors is given in the end of the paper.

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