Civil Engineering and Architecture 2(6): 251-256, 2014 http://www.hrpub.org
DOI: 10.13189/cea.2014.020603

Optimum Ductility Assessment of Earthquake Resistant Structures

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Abstract Provision of ductility in the structures according to the modern design codes lead to more economic constructions, while safety levels reach higher rates. The philosophy is based into allowing some damage to occur in predetermined elements where enough ductility has been provided in order to ensure the member's capacity during an earthquake. This research focuses on investigating optimum ductility provisions for buildings to achieve the desired performance. The aim is to assess the parameters which affect ductility demands and overall present a comprehensive methodology for evaluating the structural performance. Analytical work was based on the comparison of two 4-storey reinforced concrete buildings designed as high ductility class (DCH) and medium ductility class (DCM) upon a strong rock (Ground type A, Eurocode 8 soil classification)according to the Eurocode 8. For a fair comparison both buildings were designed to have same vibration frequencies in order to experience same energy release rates under a number of earthquakes with varied ground acceleration amplitudes and frequency spectrums. The main criteria for the comparison were: (i) the inter-storey drifts, (ii) the energy distribution among the floors, (iii) the structural damage in terms of plastic hinges initiation and ductility demand rates, (iv) total energy dissipation and (v) top floor displacements. The damage rates in the structures were found to be directly correlated to the earthquake's frequency range. Low frequency seismic events corresponding to high periods in the elastic response spectrum used for the design of the structures were more catastrophic. The paper proved that DCH buildings perform generally better than DCM for high ground acceleration amplitudes, while for smaller GAA where the responses are governed by the stiffness in the elastic response range the DCM structures have functional superiority. Higher ductility provisions have been found beneficial for the structural performance, especially for higher ductility demands caused by higher intensity earthquakes with increased return periods and ground acceleration amplitudes.

Keywords Earthquake Resistant Structures, High Ductility Class (DCH), Medium Ductility Class (DCM), Structural Performance, Inter-Storey Drifts, Energy Dissipation and Distribution, Structural Damage

1. Introduction

The modern design approach allows some local failure in pre-determined structural members to occur during an earthquake event, where extra ductility has been provided. The formation of plastic hinges at these places enables the dissipation of energy and re-distribution of moments and forces. Contrary to the Classic design the energy released from the earthquake is not totally transformed to kinetic energy of the building and the structural response in terms

of lateral acceleration and shear forces is not as high. Although that the modern earthquake resistant construction techniques through the correct detailing, the design checks and limits are being provided by the codes, there is not any clear guidance for obtaining the optimum structural performance. A high (DCH) and a medium ductility class (DCM) multi-storey building has been designed according to Eurocode 8 in this study, for assessing the importance of ductility towards the structural optimization.

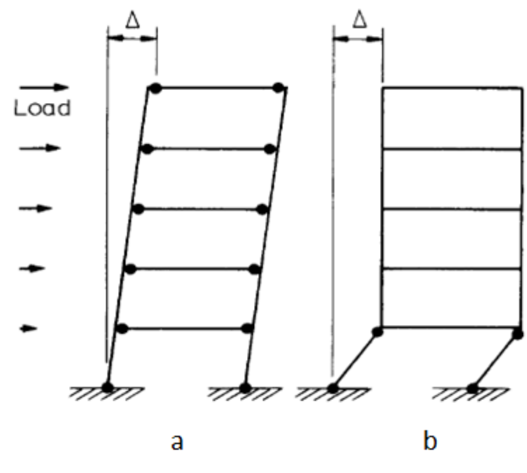

Figure 1. Sway mechanisms in laterally loaded multistorey frames, [1]

2. Seismic Design Procedures for Reinforced Concrete Buildings

The deterministic design philosophy for anti-seismic design of buildings requires that the plastic hinges will develop in ductile reinforced concrete structures and only in specific desirable locations selected by the designer. In order to ensure that the designed resistance of the structure will be maintained with negligible decay, it is of high importance to perform correct detailing and provide appropriate confinement in the plastic hinge regions [1].

According to the modern design codes, the strong column-weak beam system is preventing the creation of soft-storey mechanisms as it is shown in Figure 1, [1].

2.1. Philosophy of the Capacity Design

For preventing the soft-storey mechanism depicted in Figure 1(b) the codes have introduced the capacity design checks (Sum of column resistances > 1.3 sum of beam resistances for each node), (Eurocode 8) [2].

2.1.1 Equivalent Damping and Hysteretic Energy

A stable manner of energy dissipation should be ensured for seismic resistant structures. The chosen mechanisms during the inelastic dynamic response should maintain reasonable high levels of load resistance in several large reversed cycles of inelastic displacements with minimum loss of stiffness after each cycle [1]. One of the leading parameters optimizing the seismic performance of ductile structures is the hysteretic energy dissipation [3]. The equivalent damping coefficient and the hysteretic energy are important parameters steering to the strength requirement for a target displacement under a specific earthquake.

2.2. Detailing and Confinement

Confinement increases the load carrying capacity and strength of concrete in the confined core under compression. As the achieved strains exceed 3% in confined axially loaded specimens, larger curvature ductility can be developed in compression under both earthquake and dynamic loading, [1]. The correct bonding is also of high importance in the design of interior beam-column joints of multi-storey frames, as plastic hinges are expected in interior columns, [1].

2.3. Ductility in the Modern Earthquake-Resistant Building Design

The structures designed for different ductility classes have different performance characteristics: The structures designed for high ductility class are the most economically effective due to the largest reduction of the design seismic force (high q factor)[1]. Under an earthquake the structural system experiences large inelastic excursions and the overall damage is extensive. High ductility class (DCH) structures have lower base-shear resistance, higher damage rates, an increased displacement response and ductility demand comparing to the other two. In terms of the performance based design the difficulty for DCH to meet the displacement based design criteria is higher.

The DCL structures require relatively high resistance as the q factor and the ductility provided are small. Their responses are rather stiff due to the small yield excursion under the designed earthquakes. Main concerns are the structural vulnerability to fragility which may arise in excessive ground motions. The low ductility frames depict a worse performance, due to the crushing of concrete and buckling of the longitudinal bars at the bottom regions of the columns from insufficient confining. The hysteretic response of DCL is not usually satisfactory, as pinching in the plastic hinges occurs. Medium ductility class structures usually behave in an intermediate manner. The medium ductility class frames usually experience less damage with no obvious signs of material failure. Although their satisfactory performance due to their reduced overall damage and good hysteretic behaviour, efforts to gain enhanced ductility for the same cost should be encouraged [3].

Increasing the amount of confinement in the critical regions of columns, improves the local performance and the overall ductility through the hysteretic behaviour and increased hysteretic damping.

2.4. Performance-Based Design

The main objectives in the anti-seismic design are the immediate occupancy (IO), life safety (LS), collapse prevention (CP) in moderate and minor earthquakes and avoid collapse in a major earthquake [4]. The main concern of engineers is to validate the suitability of the selected performance levels as well as the parameters leading to the desired performance and the earthquake hazard [4]. The performance levels are governed respectively by three corresponding structural characteristics (stiffness, strength and deformation capacity), as depicted in the Fig. 2.

In the performance based design, the hazard levels correspond to a given probability of being exceeded during the life-time of the structure. It is usually assumed that the immediate occupancy corresponds to a 50% probability of exceedance, the life safety to 10%, while the collapse prevention only to 2%, [5].

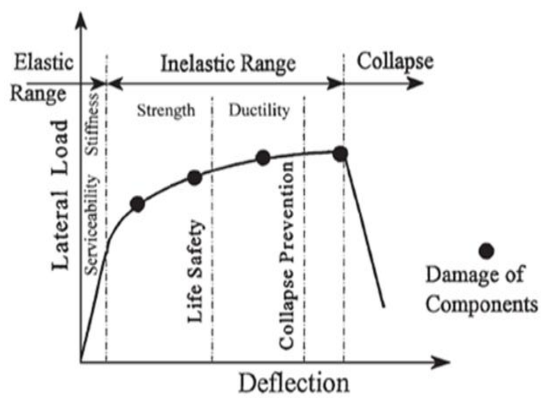

Figure 2. Typical performance curve for the structure [4]

1The q factor is used to derive the critical load that would cause damage to the structure in the elastic response spectrum. The critical load that causes failure to the same structure without ductility provisions therefore is q times higher than the corresponding to the ductile structure.

2.5. Inter-Storey Drift Profiles

Being a principal design consideration in the performance of multi-storey buildings, the inter-storey drifts account for the structural and non-structural damage of structures excited to earthquake motions [6]. The performance of multi-storey buildings is assessed on the basis of inter-storey drift values along the height of the building and can also be considered as a mean for providing uniform ductility demand over all stories. Chopra (1995) stated the importance of controlling large storey drifts which may result in a soft storey mechanism with catastrophic building collapse in a seismic event [7].

2.6. Seismic Design Procedures and Optimization

Fragiadakis et al [8] stated that the most suitable methods for evaluating the structural response against strong ground motions are the pushover and inelastic time-history analysis. The responses in both analysis are checked against acceptability limits for system elements e.g. load stability and inter-storey drift as well as in local element levels e.g. the plastic rotation of a section and the element strength [9]. The time-history analysis employed in this study through the Drain-2DX [2] programme, is capable of capturing the truebehaviour of the structure but requires excessive computational time comparing to the pushover method, as it produces results for each time step.

3. Modeling of DCH and DCM Structures

The modelling concerns two identical four-storey buildings designed according to Eurocode 8, with high (reduction factor q=5.85) and medium ductility (reduction factor q=3.9). For ensuring the same energy dissipation mechanisms and a fair comparison, the capacity design for the considered nodes has been identical, [10].

The applied loads are:

- Roof (Variable load) = 1.0KN/m^2
- Floor(Variable load)=2.5KN/m^2,φ=0.8
- Slab thickness =h_f=0.24m
- Length in plan =L_y=7m

Initially the design response spectrum has to be produced in order to correlate the peak ground acceleration for different vibration periods (T) of the structure, account the energy dissipation of the structure, and reduce the accelerations and resulting forces of the elastic spectrum.For this analysis the design spectrumfor severe earthquake loadings (Ms>5.5)has been used, [10].

The same sections with DCM have been used, resulting into the same applied actions, modal mass contributions, and viscous damping ratios etc. At the same time the same element size result in same structural stiffness and thus vibration excitation frequencies. The design is based in changing the reinforcement in critical elements for achieving a better energy distribution among the floors of the structure under an earthquake excitation. The input moments in the Drain2DX programme accounted the second order effects depending on the vibration mode. The moments of resistance fulfilled all the design requirements, (Appendix A) of [10].

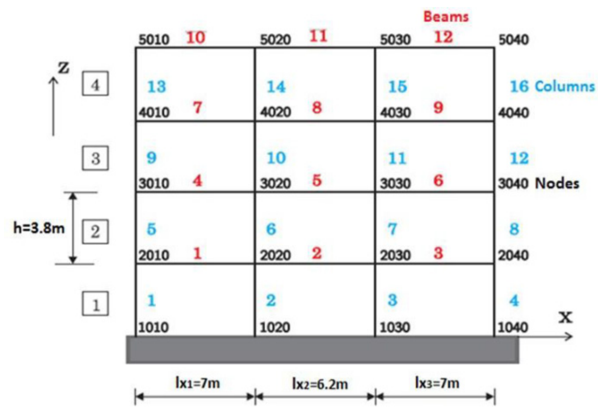

Figure 3. Plan view of the 4-storey building: The building repeats itself every 7 meters (ly=7m)

Nodes	$\Sigma M_{Rc}/\Sigma M_{Rb}$ DCH	$\Sigma M_{Rc}/\Sigma M_{Rb}$ DCM	Check if ratio>1.3
2010/2040	2.607	2.8367	OK
2020/2030	1.813	1.964	OK
3010/3040	2.33	2.4112	OK
3020/3030	1.707	1.8347	OK
4010/4040	2.33	2.3657	OK
4020/4030	1.764	1.87	OK

Figure 4. Capacity design for all nodes, with ΣM_{Rc}: Sum of the column's Moments of resistance and ΣM_{Rb}: Sum of the beam's Moments of resistance for each node respectively

It was important in the design process for performing a fair comparison to ensure that the DCM building has similar ratios with the DCH's in the capacity design or slightly higher, in order to pre-determine similar failure mechanisms.

4. Results and Discussion

The earthquake spectral amplitudes (expressing the energy release) and ground accelerations are considered in this analysis, as the two basic parameters affecting the structural performance.

5. DCH and DCM Performance in Various Earthquakes

A comparison has been made in terms of the maximum

2 DRAIN-2DX is a general purpose computer program for static and dynamic analysis of plane structures that performs nonlinear static and dynamic analyses, [11].

drift as a percentage of the limit in the primary axis for both buildings under various earthquakes. The black and red dashed lines corresponding to the secondary axis express the ratio of the spectral amplitudes for DCM/DCH buildings.

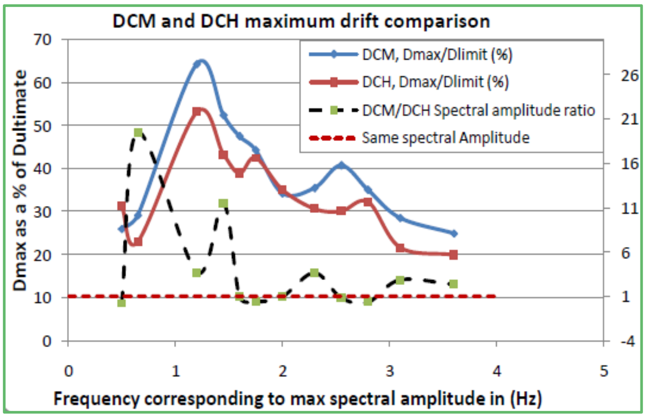

Figure 5. Maximum drift as a percentage of the limit/secondary axis: Spectral amplitude ratio vs frequency

As expected through the whole frequency range, the DCH building appears to have a better drift performance comparing to DCM's, no conclusions can be made however, as the spectral amplitudes [3] are considerably higher for DCM.

It is clearly shown, for those values closely spaced and underneath the red-dashed line, that the DCM performs slightly better (D_{max} has a smaller percentage of its limit), as a result of DCM being affected less from that specific earthquake.

The variance of the drift percentage in the primary axis depends on the peak ground accelerations of each earthquake (as the values used for plotting the above graph correspond to different seismic events), which is the other important parameter except the spectral amplitude affecting the structural performance. That explains the rapid slope among the second point (corresponding to Mexico earthquake of PGA=0.16g) and the third point corresponding to EL-Centro (PGA=0.34g).

The employed earthquakes, proved the importance of the corresponding earthquake's frequency range, releasing most of its energy, to the corresponding design acceleration value in the elastic response spectrum (ERS) used for the design. In smaller return period seismic events the buildings performed better, as their corresponding design accelerations were a lot bigger than longer periods. For longer return periods, the DCH distributes better the energy among its floors, as a result of the same corresponding design accelerations of the ERS, and the higher energy releases into the DCM. The importance of the energy release to the building's fundamental frequency has been accounted by this study analytically, expressed in energy ratios, which proves the influence of the energy release rates in the structural performance. For higher energy releases into the DCM, the DCH building performed better (in terms of drifts), while depending on the magnitude of the higher energy release into the DCH, the DCM performed occasionally better. For the purpose of the comparison, both of the buildings will be exposed to the Parkfield earthquake providing 2.67 more energy to the DCH building. The analysis will be done in this case, by modifying the ground acceleration amplitude (GAA) of this earthquake in order to assess whether that variable influences the comparison.

3Expressing the earthquakes energy releases

6. Parkfield Earthquake

Despite the fact that Parkfield releases 2.67 times more energy into the DCH building from DCM and corresponds to small return periods (where the design accelerations are higher for DCM), it is proved through this comparison that even though DCH performs better.

6.1. Parkfield - Interstorey Drifts

The inter-storey drifts as a percentage of their limitation has been plotted below for a comparison among the DCH and DCM in the original Parkfield earthquake record (PGA=0.43g).

The DCH's interstorey drifts as a percentage of the allowed are slightly smaller, indicating better structural performance for the DCH building in terms of floor drifts through the whole GAA range.

6.2. Parkfield - Energy Distribution

The maximum drift among the floors over the minimum through the whole GAA has been plotted in the y-axis for both buildings.

The DCM building appeared to have higher drift ratios from DCH, through the most of the GAA range, meaning that the earthquake's energy is distributed better in the DCH's floors.

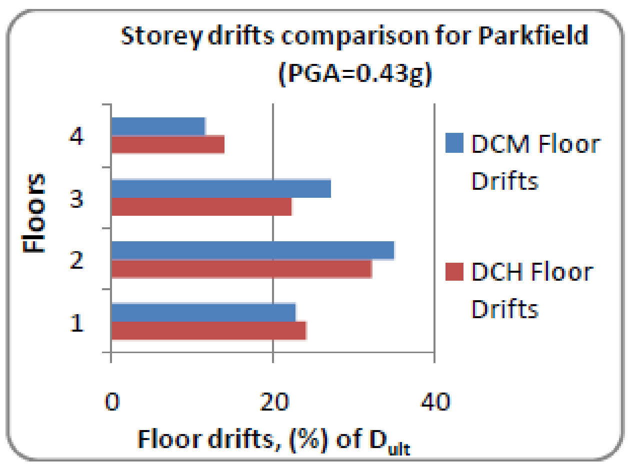

Figure 6. Drift performance comparison of DCH-DCM for Parkfield

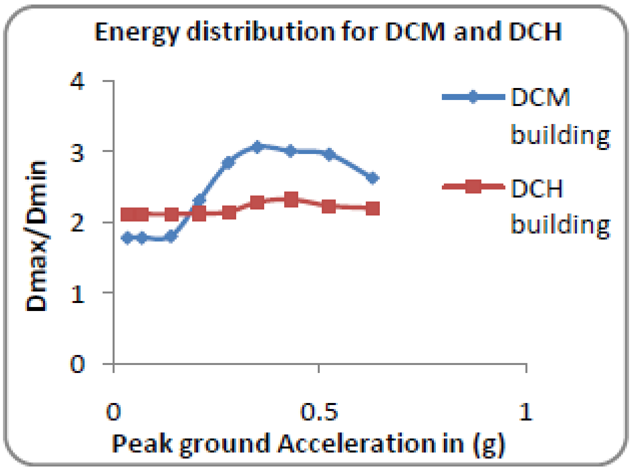

Figure 7. Energy distribution comparison in Parkfield

For smaller GAA the DCM is distributing slightly better the energy among its floors, due to its increased stiffness and thus increased ability to resist bigger earthquake loadings elastically, while the DCH is more vulnerable, deforming more and forming plastic hinges quicker and for smaller GAA. According to Figure 8, the DCM dissipates slightly higher energy rates from DCH.

6.3. Parkfield - Energy Dissipation

In the following figure the total energy dissipated by each building for various GAA of Parkfield has been plotted.

It becomes apparent that the energy dissipation is directly correlated to the damage rate, where the DCH buildings have been designed to be more efficient. The Figure 8 above proved that, in addition to the high importance of the earthquake's energy release, the GAA of the seismic event has a primary role as well. For GAA up to 0.34g, where damage has not occurred to any of the buildings, the seismic loadings are resisted within the linear elastic range (stiffness governs the responses, Figure 2). In this range the DCM dissipated more energy due to its higher stiffness. For increased GAA, with the formation of plastic hinges and structural damage, the DCH starts being more efficient due to the activation of its plastic hinges, which are dissipating more energy comparing to DCM's.

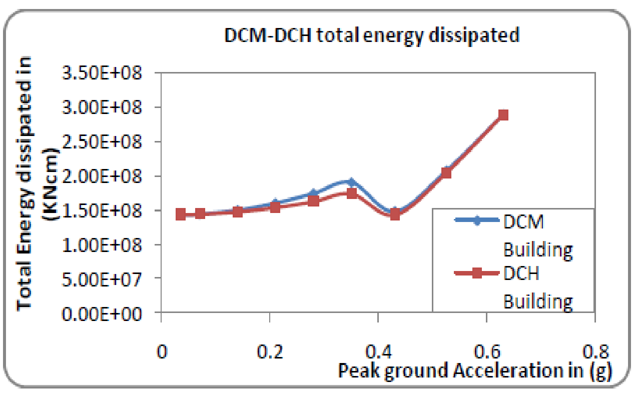

Figure 8. Total Energy dissipated comparison – Parkfield

As a result, it can be concluded, that depending on the performance objective, as described in the literature by Ahmed Ghobarah [4], the DCH's efficiency varies, with higher GAAs causing non-linear structural responses, and especially for the collapse prevention performance target, ductility governs the performance leading to the DCH's superiority.

6.4. Parkfield-Structural Damage

The ductility demands of the most critical element, beam 3010-3020 corresponding to the most energy dissipative floor (second) are expressed as a percentage of the capacity for DCH and DCM in the Figure 9.

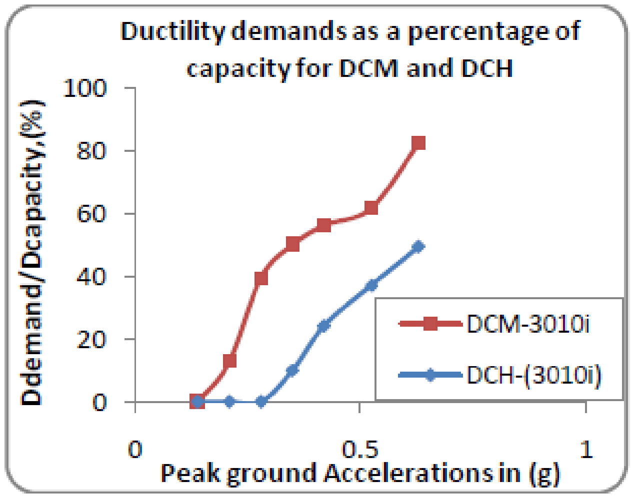

Figure 9. Ductility demands as a percentage of capacities

The increased curvature ductility capacity of DCH, resulted into the DCH's superiority in terms of the experiencing structural damage, although none of the buildings collapsed.

Although that Parkfield hits the DCH more, the DCH's curvature ductility demands as a percentage of their capacities appeared to be considerably smaller from DCM's, proving the better performance of DCH under the examined conditions, Figure 9.

7. Conclusions

Through the performance comparison of the DCM and DCH buildings, it was found that the damage rates are directly correlated to the earthquake's frequency range. Low frequency seismic events corresponding to high periods in the elastic response spectrum used for the design of the buildings were found to be more catastrophic. Independently to the frequency and the earthquake's energy release, it was proved that higher ground acceleration amplitudes worsen the structural performance. That was proved through series of figures, indicating that the floor drifts, the variance of the energy dissipation among the floors, the ductility demands and the structural damage are being increased for higher ground acceleration rates. Although Parkfield released 2.67 times more energy into the DCH building, the DCM building performed generally worse, even though its higher (by 1.46 times) designed peak ground acceleration for this frequency range in the elastic response spectrum. For smaller GAA, the DCM appeared to perform slightly better, as a result of its higher stiffness, which governs the responses for smaller GAA, Figure 2. It can generally be concluded that higher ductility provisions are beneficial for the structural performance, especially for higher ductility demands caused by higher intensity earthquakes with increased return periods and ground acceleration amplitudes.

Abbreviations

DCH: High Ductility Class, DCM: Medium Ductility Class, DCL: Low Ductility Class, ERS: Elastic Response Spectrum, GAA: Ground Acceleration Amplitude

Ground Type A: Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface, with vs,30>800) of Eurocode 8 classification scheme.

Acknowledgments

I wish to acknowledge the extensive support and guidance provided by my project supervisor Dr. MihailPetkovski during this project.

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