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# Drift-based design criteria for reinforced concrete columns and hybrid rocking columns

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ABSTRACT: Under the framework of performance-based design, several types of design criteria such as material strains and drifts are used in bridge design codes. In the current Canadian Highway Bridge Design Code, concrete and steel strain limits are used to determine damage states of columns. However, it is not clear how material strain limits are correlated to column drifts. In design practice, engineers can obtain column drifts mush easier than material strains. This study investigates drift-based design criteria for both cantilevered reinforced concrete and hybrid rocking columns by using the code defined material strain limits as the basis. For the two types of bridge columns, this study presents the drifts corresponding to code defined damage states, focusing on material strain limits. Pushover analyses of finite element models with different aspect ratios, reinforcement ratios, and axial load ratios are performed. Then, this study further investigates the drift-based design criteria for hybrid rocking columns using a similar methodology but more sophisticated analyses including both static and dynamic analyses. In the end, design charts correlating damage states and drifts are presented to assist in engineering designs.

## 1 INTRODUCTION

Performance-based seismic design has become the major design methodology in many seismic codes as it allows engineers to have better control over the structural performance and provide bridge owners with a more realistic description of the post-earthquake services. In performance-based design (PBD), various types of design criteria have been used around the globe (Zhang and Alam, 2019). Three sets of example design criteria used in performance-based design are listed in Table 1. In the Canadian Highway Bridge Design Code (CSA, 2019), material strains are used as main seismic design criteria. The code requires important bridges to be designed for multiple levels of hazards. At each level, a set of concrete and steel strains are given to limit the plastic deformation of seismic critical components. In some other jurisdictions, displacement-based or drift-based design criteria are used, where drift is the ratio of lateral deformation to member length. For example, per the South Carolina Department of Transportation (SCDOT, 2008), the displacement limit at top of columns may be defined as 0.075 H inches (H is height in feet) for moderate earthquakes (SCDOT, 2008). Drift related design criteria are widely used in the building industry (Ghobarah, 2001) but less common in the bridge industry although it has been extensively investigated. Researchers have investigated the relation between drift and certain damage states. For example, Berry and Eberhard (2003) proposed regression equations that predict drifts corresponding to longitudinal rebar buckling and concrete cover spalling. The proposed equations use basic design parameters such as reinforcement volumetric ratio, material strength, axial load, and column height as the inputs for calculating drift limits. Billah and Alam (2016) investigated the design drift limit for columns reinforced with different shape memory alloys.

Despite extensive research on the column drifts, there is yet a systematic study on the design drift limits of bridge columns considering parameters of aspect ratios, reinforcement ratios and axial load ratios. The purpose of this study is to propose design drift limits for different damage states that can be used by engineers. The basis of the damage state definition is the material strains defined in the Canadian Highway Bridge Design Code (CSA, 2019) shown in Table 1. To correlate drifts with material strains, static pushover analysis and dynamic time history analysis are performed. It is expected that by using drift limits as design criteria, it would greatly simplify the design process of most regular bridges.

In this paper, two types of bridge columns are studied: traditional reinforced concrete columns and novel hybrid rocking columns. While the reinforced concrete column is certainly the dominant earthquake resistant system, hybrid rocking column is gaining more attention both in the research community and the bridge industry. Hybrid rocking columns are usually composed of precast columns that are made continuous with adjacent members through post-tensioning tendons and energy dissipating (ED) bars. At the connections between the hybrid rocking column and beam or footing, the longitudinal rebar is often referred to as energy dissipating bars. They are usually unbonded to concrete to allow the opening of a large gap and to avoid stress concentration. The post-tensioning tendons are almost always unbonded to the concrete for the full length. The purpose of the tendons is to achieve the self-centering of the columns after earthquakes as the post-tensioning force would provide self-centering force when the column is deformed. Numerous studies have proved that hybrid rocking columns offer excellent seismic performance and have the potential to accelerate constructions (Bu, et al., 2016, Dawood, et al., 2011, Palermo, et al., 2005, Sideris, et al., 2014, Wang, et al., 2018).

Table 1. Design criteria.

| Ghobarah (2001) | | CSA (2019) | | Hwang et al. (2001) | |
|---|---|---|---|---|---|
| Damage states | Drift | Damage states | Material strain | Damage states | Displacement |
| No damage | 0.2% | Minimal damage | Concrete strains ≤ 0.006<br>Steel strains ≤0.01 | Slight damage | First yield displacement |
| Repairable damage | 0.5% | Repairable damage | Steel strains ≤0.025 | Moderate damage | Global yield displacement |
| Irreparable damage | 1.5% | Extensive damage | Concrete core ≤ 80% ultimate strain<br>Steel strains ≤0.05 | Extensive damage | Displacement when concrete strain equals to 0.002 |
| Near collapse | 2.5% | Probable replacement | Crushing of concrete core<br>Steel strains ≤0.075 | Complete damage | Maximum displacement |

## 2 FINITE ELEMENT MODEL

Finite element analyses are performed in this study to correlate damage states with drifts. Before using the finite element models for the parametric study, they are first validated against experimental studies. In this research, SeismoStruct (SeismoSoft, 2020) is used to simulate both the reinforced concrete column and the hybrid rocking column. The software has been extensively used by other researchers in simulating traditional reinforced columns and columns with new materials including FRP and shape memory alloys (Billah and Alam, 2012, Calvi, et al., 2008, Zhang, et al., 2016).

The modeling of the reinforced concrete column is well-established; thus, this paper does not elaborate more on this topic. The focus of this section is on the modeling of the hybrid rocking column, which can be sophisticated as has been done by several researchers (Salehi and Sideris, 2016, Trono, 2014). This study uses a relatively simple yet accurate approach, which can be achieved by general structural software without extensive calibrations. A cantilever hybrid rocking column model used in this study is illustrated in Figure 1. In this model, an artificial unreinforced column segment is created at the bottom of the column. The top node of the unreinforced column segment constrains the top node of the ED bars. The lengths of the unreinforced column segment and the ED bar equal to the length of unbonded longitudinal rebar in the actual column design. An elastic element overlapped with the column element is used to simulate the unbonded tendons.

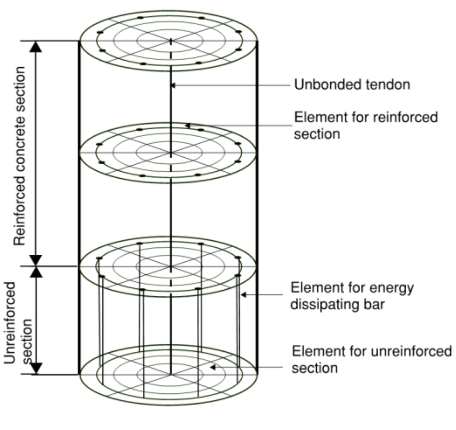


Figure 1. Finite element model of the hybrid rocking column.

Finite element models are validated based on the experimental study of cyclic static loading by Cohagen, et al. (2008). Cohagen, et al. (2008) tested hybrid rocking columns under reversed cyclic static loading. When constructing the columns, the authors used six large diameter bars as ED bars connecting the footing and the column. The ED bars were unbonded from the column-footing interface to 203 mm depth into the footing. Unbonded post-tensioned Williams bar was used to achieve the self-centering behavior. The major column parameters are presented in Table 2.

Table 2. Testing column parameters.

| Reference | Height (mm) | Diameter (mm) | Total Axial Load Ratio | ED Bar Unbonded Length (mm) |
|---|---|---|---|---|
| Cohagen, et al. (2008) | 1500 | 500 | 0.12 | 203 |

The comparison between simulation and static testing results by Cohagen, et al. (2008) is presented in Figure 2. The finite element model captures the initial and post-elastic stiffness as well as strength very well even at extreme deformation up to 10% drift. It is noted that the strength degradation is gradual and ductile, energy dissipation is satisfactory and the hysteresis loop is stable.

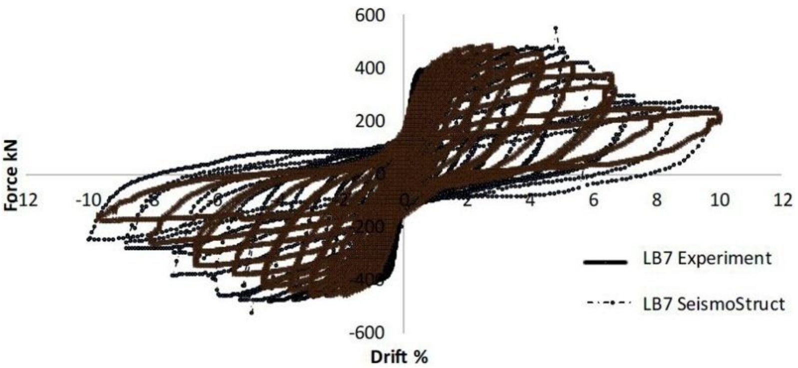


Figure 2. Validation of hybrid rocking column model under static loadings.

## 3 SEISMIC DESIGN PARAMETERS

The seismic performance of flexural members is largely dominated by a few normalized parameters: aspect ratio, reinforcement ratio, and axial load ratio. The aspect ratio is the ratio of column height to its diameter, which determines how slender the member is. Slender members usually have higher lateral deformation capability compared with squat members. The reinforcement ratio is the volumetric ratio of rebar to the concrete, which is an important factor deciding the bending moment capacity of the section. For hybrid rocking columns, the term reinforcement ratio does not include any considerations of the tendons. It is purely the ratio between longitudinal rebar (ED bar) area and column cross-section area. The axial load ratio is defined as the ratio of axial loading to the concrete section axial resistance. In the case of the hybrid rocking column, the term total axial load ratio is used when the axial load is caused by both superstructure dead load and post-tensioning force. Excessive axial load ratios tend to cause compressive damage and reduce ductility.

Table 3 summarizes the parameters and their ranges studied in this paper. For reinforced concrete columns, three parameters are examined at three levels that cover most of the typical bridge columns. An aspect ratio of 10 represents a slender column and a ratio of 3 represents a short column. Axial load ratios of most bridges in moderate to high seismic regions are around 10%, and usually not less than 5% and not more than 20%. The rebar ratio of most bridge columns ranges between 1% to 2%. Overall, the three parameters at three levels represent 27 column designs. For hybrid rocking columns, the same three parameters are investigated, but at slightly different levels for axial load ratio and reinforcement ratio (ED bar ratio). Hybrid rocking columns are normally subjected to higher total axial load ratios because of the combination of dead load and post-tensioning force. Therefore, only two levels of total axial load ratios are studied, which are 10% and 20%. In this study, the dead load and post-tensioning force are set to equal, both of which contribute to half of the total axial load. In terms of reinforcement ratio, hybrid rocking columns often have less rebar (ED bar) compared with the reinforced concrete columns. This is because the moment capacity is contributed by both the tendon and the rebar. An excessive amount of rebar would reduce the re-centering capacity of the column and increase construction costs. Thus, for hybrid rocking columns, this study investigated one parameter at three levels and two parameters at two levels, the overall combinations generate 18 column designs.

Table 3. Column design parameters.

| Reinforced concrete column | | | Hybrid rocking column | | |
|---|---|---|---|---|---|
| Aspect ratio | Axial load ratio | Reinforcement ratio | Aspect ratio | Total axial load ratio | ED bar ratio |
| 3 | 0.05 | 0.01 | 3 | 0.1 | 0.005 |
| 6 | 0.1 | 0.015 | 6 | 0.2 | 0.01 |
| 10 | 0.2 | 0.02 | 10 | NA | NA |

## 4 DRIFT-BASED DESIGN CRITERIA FOR RC COLUMN

The major benefit of using drift-based design criteria is that it can simplify the structural design process, especially during the preliminary design stage. With drift limits in mind, engineers would not have to perform non-linear analysis to obtain material strains to determine damage states. However, the challenge of using drift limits as design criteria is that the limit varies with structural systems and several column parameters. In this section, the drift limits correspond to different damage states defined in the Canadian Highway Bridge Design Code (CSA, 2019) are calculated based on non-linear pushover analyses. The analyzed columns are cantilevered and have varying parameters described in Table 3. Based on the pushover analysis results, charts connecting drifts with damage states in Figure 3 are produced. Figures 3 a, c and e correlate drift with concrete damage states, considering aspect ratios of 3, 6 and 10. Figures 3 b, d, and f correlate drift with rebar damage states for the same three aspect ratios. In each of the charts, two other variables axial load ratio (P) and rebar ratios are included.

In Figures 3 a, c and e, it is noted that the plotted lines are generally discrete in the vertical direction, whereas the lines in Figures 3 b, d and f are grouped based on the level of damage (minimal, repairable and extensive damage). This is because the concrete damage states (Figures 3 a, c and e) are more sensitive to the axial load ratios. Thus different axial load levels generate different drift limits. Axial load ratios do not seem to affect rebar damage states significantly (Figures 3 b, d and f). Therefore, the drift limits corresponding to rebar damage with different axial load ratios seem to be similar. Another finding from Figure 3 is that all the lines from 1% to 2% rebar ratio are relatively flat, meaning that drift limits as design criteria are not very sensitive to rebar ratio. In most cases, the drift limit has less than 1% difference irrespective of the rebar ratio conditioned on the same axial load and aspect ratio. It is also noted that for columns with aspect ratios greater than 6, the extensive damage states of rebar do not occur even at very large drift levels.

It is noted that the aspect ratio is the most significant factor affecting the drift limits. The effects of rebar ratio and axial load ratios are relatively smaller. Therefore, it may be appropriate to propose design criteria solely based on aspect ratio by taking the average effect of rebar ratio and axial load ratio. These simplified design limits may be used for preliminary design. Table 4 presents the drift limits for reinforced concrete columns with three levels of aspect ratios. The corresponding standard deviation resulted from various levels of axial load ratios and rebar ratios are also presented.

Table 4. Average reinforced concrete column drift limits based on static analysis.

| Aspect ratio | Drift | Steel strain, $\varepsilon s$: 0.01 | Concrete strain, $\varepsilon c$: 0.006 | Steel strain, $\varepsilon s$: 0.025 | Concrete core strain, $\varepsilon c$: 0.008 |
|---|---|---|---|---|---|
| 3 | Average | 0.83% | 1.16% | 1.62% | 1.80% |
| | Standard deviation | 0.04% | 0.19% | 0.07% | 0.38% |
| 6 | Average | 1.79% | 2.33% | 3.53% | 3.70% |
| | Standard deviation | 0.09% | 0.39% | 0.12% | 0.78% |
| 10 | Average | 3.19% | 3.93% | 6.32% | 6.39% |
| | Standard deviation | 0.17% | 0.58% | 0.27% | 1.26% |

## 5 DRIFT-BASED DESIGN CRITERIA FOR HYBRID ROCKING COLUMN

Several design methods of hybrid rocking columns were proposed by researchers (Pampanin, et al., 2001, Rahmzadeh, et al., 2018). The drift-based design criteria proposed in this paper are additional tools for checking structural performance. The drift limits are corresponding to the strain-based criteria presented in Table 1. It should be noted that the damage states studied in this paper do not include tendons and shear damage. Tendons are expected to behave elastic and shear resistance of the column should be capacity protected. Engineers should always make sure flexure damage occurs before brittle damage.

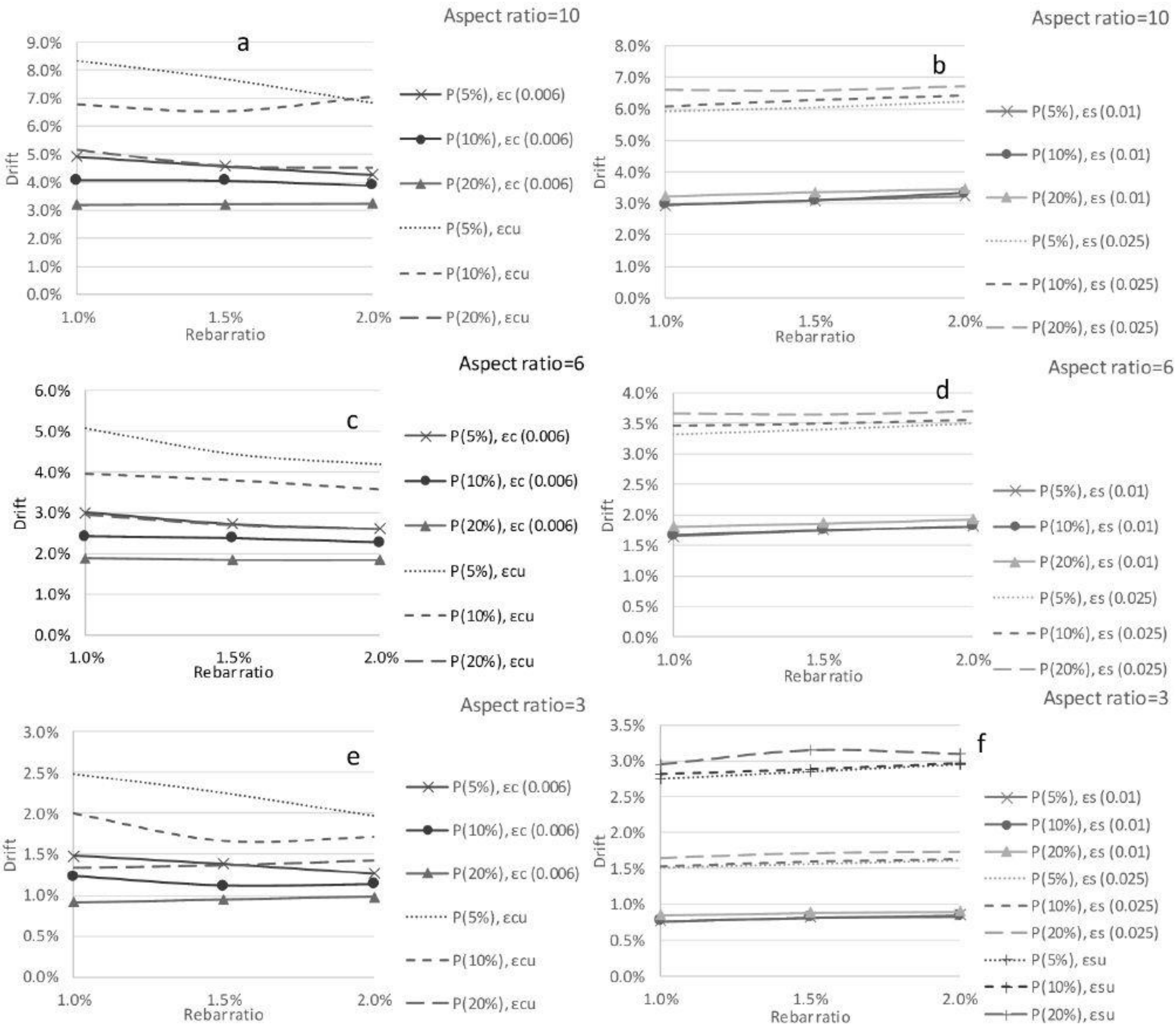


Figure 3. Drift – material strain relations of reinforced concrete columns.

In the analyzed hybrid rocking columns, it is assumed that the longitudinal reinforcement (ED bars) are unbonded for a length equal to the plastic hinge length of an equivalent reinforced concrete column. If engineers decide to increase the unbonded length, it is possible to further reduce the damage in the ED bars as stress will be distributed to an even longer length. Besides, it is assumed that the axial dead load and post-tensioning force are equal in each column design. The reported axial load ratio is the total axial load ratio including both dead load and post-tensioning force. Under these conditions, hybrid rocking column drift – material strain relations are presented in Figure 4. These results are based on the non-linear static analysis under reversed cyclic loadings. Like the charts for reinforced concrete columns, it is noted that the lines in Figure 4 also have relatively small slopes, which means that the effect of the reinforcement ratio on the drift limit is small.

To present hybrid rocking column results in a more consolidated way, average drift limits for three levels of aspect ratios are presented in Table 5. Standard deviations are also presented and they are relatively small compared with the average values.

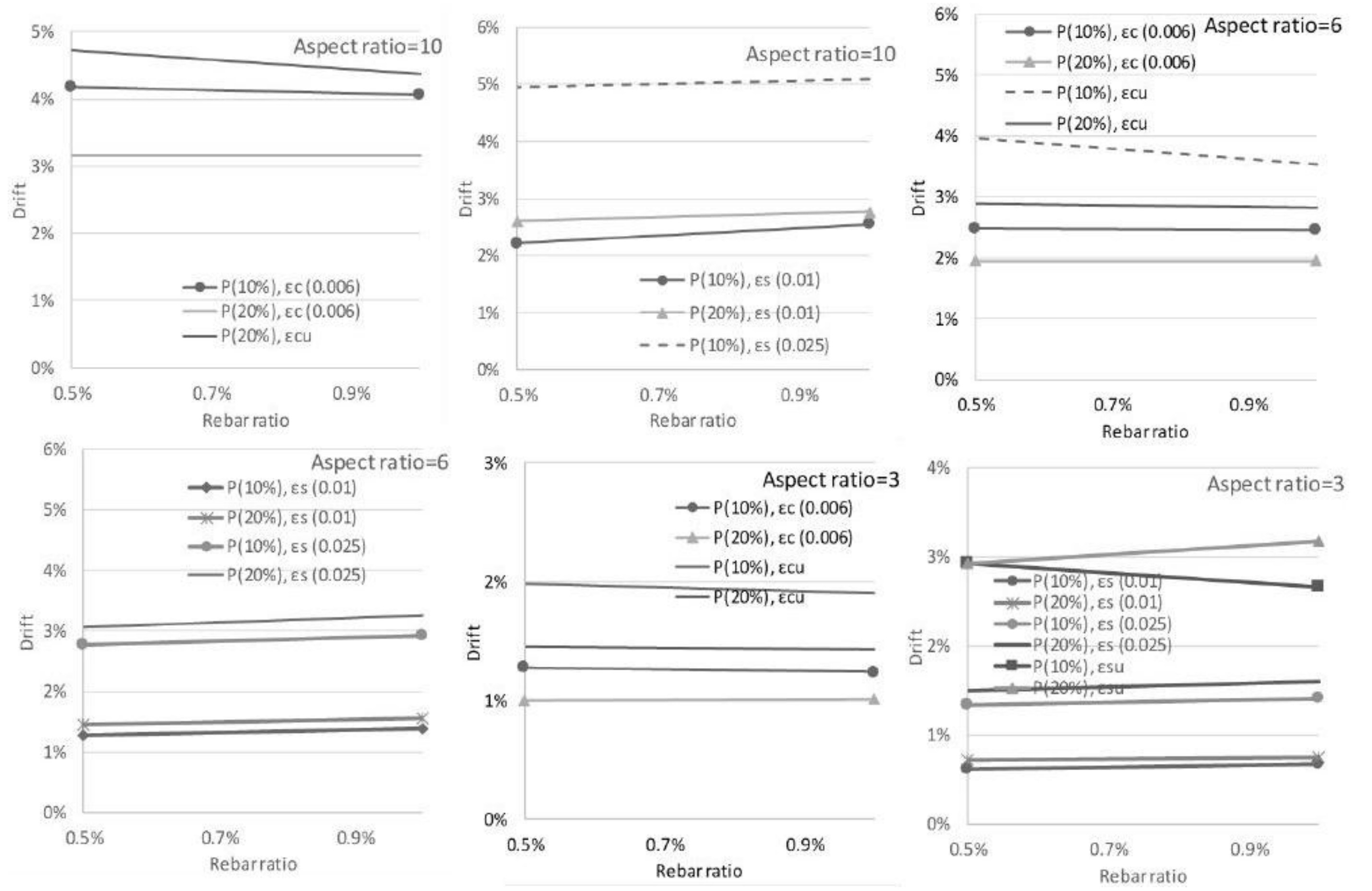


Figure 4. Drift – material strain relations of hybrid rocking columns.

Table 5. Average hybrid rocking column drift limits based on static analysis.

| Aspect ratio | Drift | Steel strain, εs: 0.01 | Concrete strain, εc: 0.006 | Steel strain, εs: 0.025 | Concrete core strain, εc: 0.008 |
|---|---|---|---|---|---|
| 3 | Average | 0.69% | 1.14% | 1.46% | 1.69% |
| | Standard deviation | 0.05% | 0.12% | 0.10% | 0.25% |
| 6 | Average | 1.41% | 2.21% | 3.01% | 3.30% |
| | Standard deviation | 0.10% | 0.26% | 0.18% | 0.48% |
| 10 | Average | 2.54% | 3.64% | 5.02% | 4.55% |
| | Standard deviation | 0.20% | 0.48% | 0.08% | 0.18% |

After finishing nonlinear static analysis, nonlinear dynamic time-history analyses were performed on hybrid rocking columns to confirm the results from static analysis. In the time history analysis, 12 motions are used and each of the motion is scaled to three levels. Thus, there are 36 runs of time history analyses for each of the hybrid rocking column. Table 6 presents the ground motions used in this study and Figure 5 plots the acceleration response spectra of original ground motions. In each time history analysis, the time steps of reaching specific material strains are recorded. Then based on recorded the time steps, maximum drifts prior to the recorded time step are extracted.

As has been discussed, it may be appropriate to simply use average drift limits ignoring effects from axial load ratio and ED bar ratio for preliminary design. After extracting the drifts corresponding to various damage states from each of the time history analysis, the average drifts from all motions are summarized in Table 7. In the time history analysis, the steel strain limit of 0.05 is rarely reached, therefore no corresponding drift is included in Table 7.

## 6 DESIGN RECOMMENDATIONS

Based on finite element analyses, this study proposes drift-based design criteria for cantilevered reinforced concrete columns and hybrid rocking columns. These drift limits are to be compared with the displacement demands at various hazard levels to ensure columns are within the specified minimal, repairable and extensive damage states described in Table 1. As has been presented in previous sections, average drift limits for different axial load and rebar ratio have small coefficients of variation. The sequence of the damage is generally consistent in all the analyzed columns, from the beginning to the end, the steel strain of 0.01 occurs first, then the concrete strain of 0.006, followed by steel strain of 0.025 and concrete core crushing. Based on the static analysis of reinforced concrete column and dynamic analysis of hybrid rocking column, Figure 6 and Figure 7 are proposed for assisting engineering design, which plots average drift limits minus one standard deviation. In the two figures, the vertical axis is the design drift limit, damage states are identified on the horizontal axis. Each of the charts includes aspect ratios from 3 to 10. As the finite element models have only included aspect ratios of 3, 6 and 10, results for other aspect ratios are based on linear interpolations.

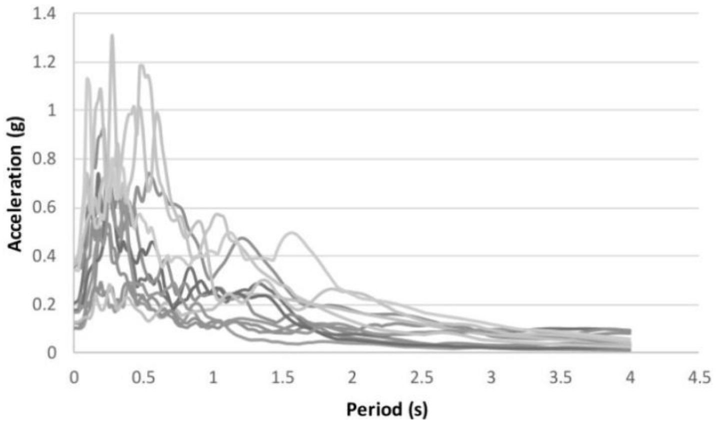


Figure 5. Response spectra of selected ground motions.

Table 6. Earthquake records.

| Event | Year | M | Station | R (km) | PGA (g) |
|---|---|---|---|---|---|
| Loma Prieta | 1989 | 6.9 | Agnews State Hospital | 28.2 | 0.172 |
| Northridge | 1994 | 6.7 | Canoga Park - Topanga Can. | 15.8 | 0.489 |
| Borrego Mountain | 1968 | 6.8 | El Centro Array #9 | 46 | 0.13 |
| Loma Prieta | 1989 | 6.9 | APEEL 2E Hayward Muir Sch. | 57.4 | 0.171 |
| Coalinga | 1983 | 6.4 | Pleasant Valley P.P. - bldg | 8.5 | 0.38 |
| Imperial Valley | 1979 | 6.5 | Aeropuerto Mexicali | 8.5 | 0.327 |
| Northridge | 1994 | 6.7 | Bell Gardens - Jaboneria | 46.6 | 0.098 |
| Northridge | 1994 | 6.7 | LA - Pico &Sentous | 32.7 | 0.186 |
| Northridge | 1995 | 6.7 | LA - E Vernon Ave. | 39.3 | 0.153 |
| San Fernando | 1971 | 6.6 | LA - Hollywood Stor Lot | 21.2 | 0.21 |
| Superstition Hills | 1987 | 6.7 | El Centro Imp. Co. Cent | 13.9 | 0.358 |
| Superstition Hills | 1987 | 6.7 | Westmorland Fire Station | 13.3 | 0.211 |

Table 7. Average hybrid rocking column drift limits based on dynamic analysis.

| Aspect ratio | Drift | Steel strain, εs: 0.01 | Concrete strain, εc: 0.006 | Steel strain, εs: 0.025 | Concrete core strain, εc: 0.008 |
|---|---|---|---|---|---|
| 3 | Average | 1.04% | 1.10% | 1.73% | 1.62% |
| | Standard deviation | 0.72% | 0.13% | 0.65% | 0.21% |
| 6 | Average | 1.37% | 2.10% | 3.00% | 3.34% |
| | Standard deviation | 0.39% | 0.49% | 0.84% | 0.57% |
| 10 | Average | 2.55% | 3.68% | 5.64% | 5.43% |
| | Standard deviation | 0.34% | 1.06% | 0.81% | 0.82% |

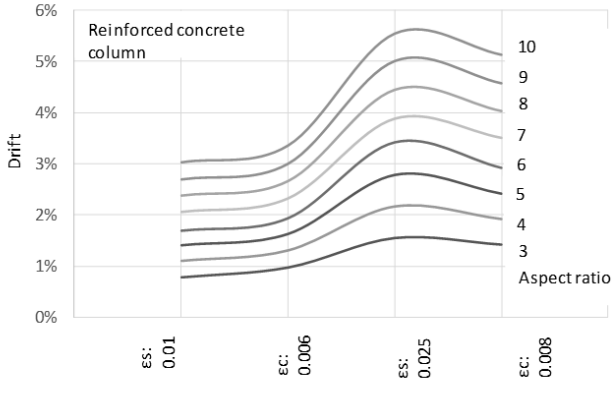


Figure 6. Reinforced column drift vs. damage states.

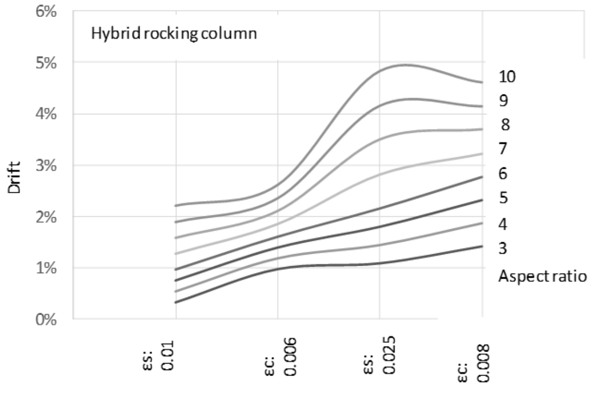


Figure 7. Hybrid rocking column drift vs. damage states.

## 7 CONCLUSIONS

This study first validates finite element models based on two experimental studies. It is shown that the simplified modeling approach is valid. Using the finite element analysis, a parametric study is performed on both reinforced concrete columns and hybrid rocking columns. Charts correlating drift limits with damage states are presented based on the damage definitions in the Canadian Highway Bridge Design Code(CSA, 2019). It is noted that aspect ratios have the most significant impact on drift limits for both reinforced concrete and hybrid rocking columns. The influence of the reinforcement ratio and axial load ratio is relatively small.

In reinforced concrete column design, it is often expected that when the material strains are limited to code specified values, the overall strength reduction is also guaranteed. For example, the strength reduction would be within 10% for repairable damage and 20% for extensive damage. However, analysis results show that it is not true for slender columns. Using columns with an aspect ratio of 10 as an example, the column reaches extensive damage states at about 5% drift, while the 20% strength reduction already occurs at about 3% drift. In the end, two design charts are proposed for preliminary engineering designs. The two charts are based on the average drifts of different rebar ratio and axial load, minus one standard deviation. Engineers would be able to determine design drift limits simply based on the damage states and the cantilevered column aspect ratio.

## ACKNOWLEDGEMENTS

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