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Technical Note

Are There Any Differences in Seismic Performance Evaluation Criteria for Concrete Arch Dams?

Heshmati, M.[1] , Hariri-Ardebili, M.A.[2], Seyed Kolbadi, S.M.[3] and Mirzabozorg, H.[4*]

[1] MSc, K. N. Toosi University of Technology, Tehran, Iran.
[2] PhD Student, Research Assistant, University of Colorado, Boulder, USA.
[3] MSc, K. N. Toosi University of Technology, Tehran, Iran.
[4] Associate Professor, K. N. Toosi University of Technology, P. O. Box: 15875- 4416, Tehran, Iran.

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ABSTRACT: Differences between stress-based and strain-based criteria are investigated in seismic performance evaluation of the arch dams in time domain. A numerical model of the coupled dam-reservoir-foundation system is prepared with the finite element technique. Reservoir is modeled using the Eulerian approach as a compressible domain, and the foundation rock is assumed to be massless. Dynamic equilibrium equations for the coupled system are solved using Newmark's time integration algorithm. Seismic performance of the arch dam is evaluated according to parameters such as demand-capacity ratio, cumulative inelastic duration and overstressed (or overstrained) areas obtained from linear elastic analyses. The results show, although there are some similarities between stress-based and strain-based criteria, evaluation of the performance based on the strain gives different results which can be led to different decision making in dam safety related projects.

Keywords: Arch Dam, Cumulative Inelastic Duration, Demand-Capacity Ratio, Seismic Performance Evaluation, Strain-Based Criteria.

INTRODUCTION

Several researchers such as Ghanaat (2002 and 2004); Fok and Chopra (1986); Yamaguchi et al. (2004), Bayraktar et al. (2009), and Hariri-Ardebili et al. (2011) have investigated seismic performance of concrete arch dams. Hall et al. (1999) proposed some indices for systematic comparison of various ground motions effects. Ghanaat (2002) proposed a methodology for damage estimation in concrete dams which can be found in the USACE (2007) guideline. Hariri-Ardebili et al. (2013) investigated the effect of water level on the dynamic performance of arch dams. Wieland and Fan (2004), and Wieland et al. (2003) investigated the behavior of concrete dams under recent earthquakes. Studer (2004) studied seismic performance of new and existing dams using methods proposed by international committee of large dams. Yamaguchi et al. (2004) discussed the role of nonlinear dynamic analyses in seismic evaluation problems of 2D concrete gravity dams. Also, Hariri-Ardebili and Mirzabozorg (2011) studied seismic performance of concrete arch dams using

* Corresponding author E-mail: mirzabozorg@kntu.ac.ir

real ground motions and endurance time acceleration functions.

As seen, all previous researches utilize the stress to determine seismic behavior of concrete dams. However, it's important to note that concrete behavior is based on the strain. In the present paper, the common criteria for seismic assessment of concrete arch dams, which are based on the stress, are substituted by similar criteria based on the strain rule. A high concrete arch dam is modeled for this purpose and evaluated using stress-based and strain-based rules. The results are compared with each other using the parameters such as the demand-capacity ratio, cumulative inelastic duration and percentage of overstressed (or overstrained) areas within the dam body.

BEHAVIOR OF MASS CONCRETE

A typical tensile stress-strain diagram of mass concrete can be divided into three parts. In the first section, in which concrete behaves as a linear elastic (LE) material, the dam is called to have serviceability performance. The second part is inelastic-strain hardening range which is known as damage control phase and causes only limited inelastic behavior in the dam body. In this state, damage may be significant but all cracking and joint openings are limited and discrete (Ghanaat, 2002). A LE analysis combined with a predefined performance evaluation criterion can be used to assess the dam response in the damage control phase. The dam response beyond the damage control range is followed by a complete loss of strength, sliding, and nonlinear response behavior of discrete blocks bounded by opened joints and cracked sections, which is called as collapse prevention performance. This behavior must be evaluated using nonlinear time-history analysis (USACE, 2007).

METHODOLOGY OF PERFORMANCE EVALUATION

In the proposed methodology, first the numerical model of the coupled system is prepared and a bunch of site-specific ground motions are selected at the desired seismic performance level. The coupled system is then analyzed and the pre-defined responses are extracted. Seismic performance of concrete arch dams is evaluated in accordance with displacements, stresses, strains, demand-capacity ratio, cumulative inelastic duration and spatial extension of overstressed (or overstrained) areas ($A^{overstress}$ or $A^{overstrain}$) on the upstream (US) and downstream (DS) faces of the dam body.

For arch dams where high stresses and strains are usually oriented in the arch and cantilever directions, the demand-capacity ratio (DCR) refers to the ratio of calculated arch or cantilever stress (or strain) to the tensile strength of mass concrete or its equivalent strain, but it can also be developed for principal stresses or strains (Ghanaat, 2002). The tensile strength of mass concrete used in computation of the DCR is obtained from uniaxial splitting tension tests or from the Raphael proposed diagram (Raphael, 1984). In the method proposed by the USACE, the mass concrete is assumed as a homogeneous isotropic material and so its properties in three principal directions are the same. The static tensile strain of the concrete is calculated at the end of the linear part of stress-strain curve, where, in fact, the serviceability performance range is only considered. The strains in the dynamic range are approximately time-independent and are calculated using the dynamic modulus of elasticity and Poisson's ratio of concrete.

The cumulative inelastic duration (CID), which is a measure of energy, accounts for magnitudes as well as the duration of stress (or strain) excursions. It refers to the total duration of stress (or strain) excursions above a stress (or strain) level associated with a certain DCR. The performance threshold curve (PTC) for arch dams is shown in Figure 1 (USACE, 2007). Also, the introduced damage criteria require to be bounded in limited areas, so that evaluation based on the LE analysis is still valid. If the spatial extent of damage or nonlinear response is limited to 20% of the total areas on the upstream or downstream faces, the LE analysis is valid (USACE, 2007). Finally, it's required to quantification of the aforementioned limit-states in order for interpretation of the results. This method uses a combination of all previously defined criteria in conjunction with the LE analysis for both stress-based and strain-based rules. Table 1 represents the tabular form of the introduced criteria for performance evaluation of arch dams.

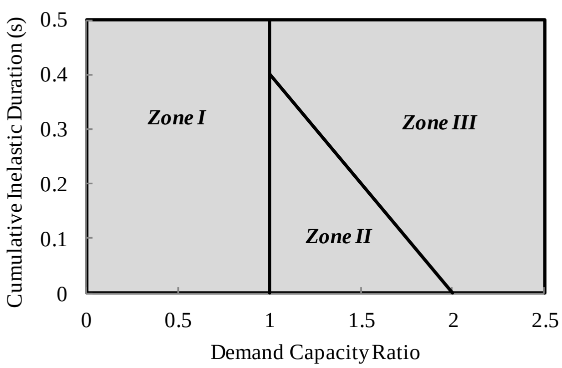


Fig. 1. Zoning the CID-DCR diagram and PTC for arch dams.

CASE DESCRIPTION

Dez double curvature arch dam is selected as the numerical example. Total height of the dam is 203 m but the height above its concrete plug (the simulated dam) is 194 m. A rectangular shaped massless foundation (Hariri-Ardebili and Mirzabozorg, 2012 and 2013) is used in this case while the reservoir length modeled is about five times of the dam height. The provided finite element model is shown in Figure 2. Modulus of elasticity of mass concrete in static and dynamic conditions is 40 GPa and 46 GPa, respectively. Poisson's ratio is 0.2 and 0.14 in static and dynamic conditions. Mass density of concrete is 2400 kg/m^3. Tensile and compressive strength of concrete are 3.4 MPa and 35.0 MPa, respectively. Thermal expansion coefficient of mass concrete is 6×10^{-6}/°C. Deformation modulus of foundation rock in saturated and unsaturated conditions is 13 GPa and 15 GPa, respectively. Poisson's ratio of rock is 0.25 (Hariri-Ardebili et al., 2011). The reservoir water density is taken as 1000 kg/m^3, the sound velocity is considered 1440 m/s in water and the wave reflection coefficient for the reservoir around boundaries is taken 0.8, conservatively.

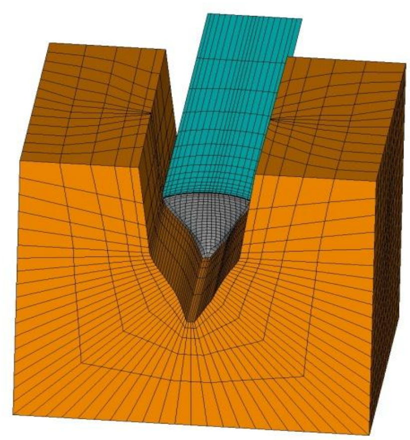


Fig. 2. Finite element model of the dam-reservoir-foundation system.

Table 1. Quantifying the limit-states.

Limit-states	DCR		DCR-CID Diagram		$A^{overstress}/A^{overstrain}$
Minor or No Damage	DCR≤1.0	&	Zone I	&	0.0%
Acceptable Level of Damage	1.0<DCR<2.0	&	Zone II	&	≤20.0%
Severe Damage	DCR≥2.0	or	Zone III	or	>20.0%

The applied loads are the dam body self-weight, hydrostatic pressure in summer condition (normal water level), thermal loads (summer temperature) and finally seismic loads based on seismic hazard analysis of the dam site. Nine ground motions are used for analysis of Dez Dam (Table 2). All ground motions are scaled based on the horizontal and vertical components of the design response spectra (Mirzabozorg et al., 2012) at the design base level (DBL) considering 5% for damping (USACE, 2007; Zhang et al., 2009; Chen et al., 2012). The Newmark-β time integration method is utilized to solve the coupled problem of the dam-reservoir-foundation model, and finally, the system is excited at the foundation boundaries using the scaled earthquake records (Hariri-Ardebili et al., 2012). It should be mentioned that the spatial varying effects of the ground motions due to coherency and wave passage were neglected in the current study (Mirzabozorg et al., 2012).

Table 2. Selected ground motions.

No.	Earthquake Name	Station
1	DUZCE	1061 Lamond station
2	LOMA-PRIETA	47006 Gilroy-Galivan Coll station
3	MANJIL	Abbar station
4	NORTH RIDGE 1	24088 Pacoima Kagel Canyon station
5	NORTH RIDGE 2	90059 Burbank Howard Rd station
6	QAEN	Qaen station
7	SAN FERNANDO	128 Lake Hughes # 12 station
8	SPITAK	Gukasyan station
9	TABAS	Tabas station

RESULTS

Figure 3 represents time-history of the first principal stress (or strain) for the most critical point of the dam body in conjunction with DCR=1.0 criterion. Although, there is some similarity between the stress and strain time-histories for each ground motion, the time in which the first cycle exceeds DCR=1.0 is different. Table 3 summarize the time in which the first point of stress (or strain) time-history reaches the predefined criterion.

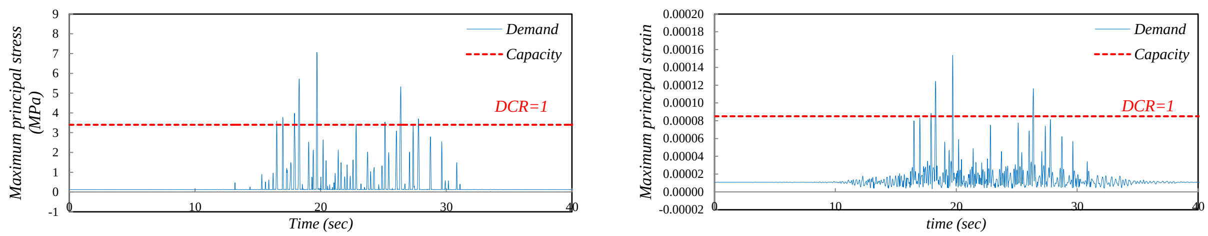
Figure 4 represents the performance curves in term of CID-DCR for both the stress- and strain-based methods corresponding to the various DCRs. Generally, the strain-based method leads to lower values for cumulative inelastic duration in comparison with the stress-based method. Considering the predefined threshold curve in Figure 1, it can be seen that using the stress-based approach leads to generation of performance curves that their mean curve is very close to the threshold while using the strain-based approach generates a set of curves in which both the mean and the mean ± standard deviation curves are below the threshold. So, evaluation of the results using the stress-based approach is more conservative than the strain-based approach. Moreover, the stress-based approach leads to the curves with some kinds of dispersion and irregularities.

Figure 5 shows the percentage of overstressed and overstrained areas on the upstream face of the dam body. As mentioned before, the acceptable value of overstressed and overstrained areas for linear analysis of arch dams is 20% and this criterion is satisfied in all cases in the DBE excitation level. The extension of overstressed (or overstrained) areas on the downstream face is more than those on the upstream face (figure not shown here). The percentage of overstressed (or overstrained) areas on the downstream face is more than those on the upstream face for lower DCRs (like DCR=1.0 and 1.1), whereas in the intermediate range of DCRs, the percentage of overstressed (or overstrained) areas on the downstream face falls suddenly, while the upstream face experiences overstressed (or overstrained) regions for all ranges of DCR from 1.0 to 2.0 and even over 2.0 (DCR>2.0). Also, using the strain-based method decreases the percentage of critical areas.

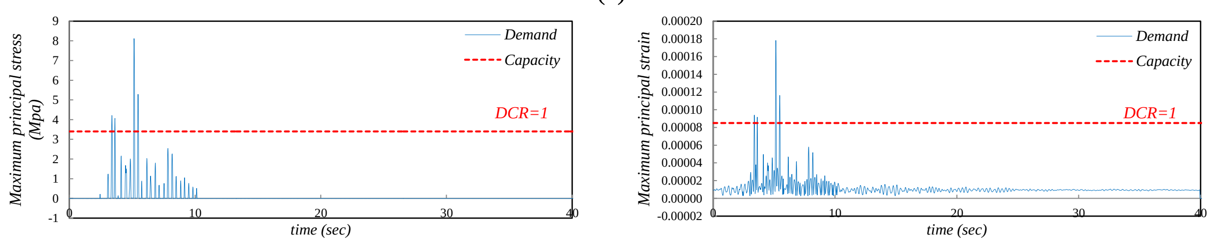
Table 3. Critical times in stress-based and strain-based methods.

Ground motion No.	1	2	3	4	5	6	7	8	9
Stress-based	16.50s	3.36s	6.52s	3.96s	3.64s	4.82s	1.68s	10.98s	10.78s
Strain-based	17.92s	3.38s	6.54s	4.90s	3.64s	4.78s	1.68s	11.26s	10.78s

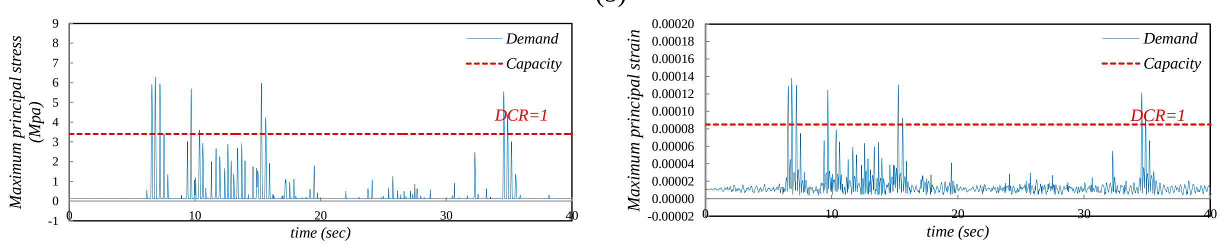
STRESS-BASED STRAIN-BASED



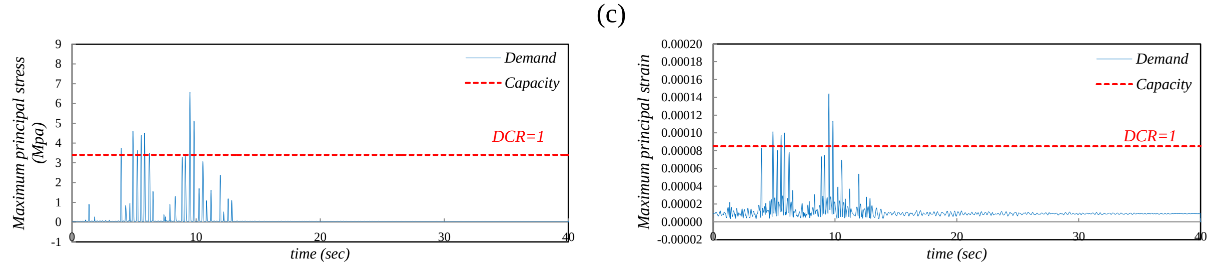
(a)



(b)



(c)



(d)

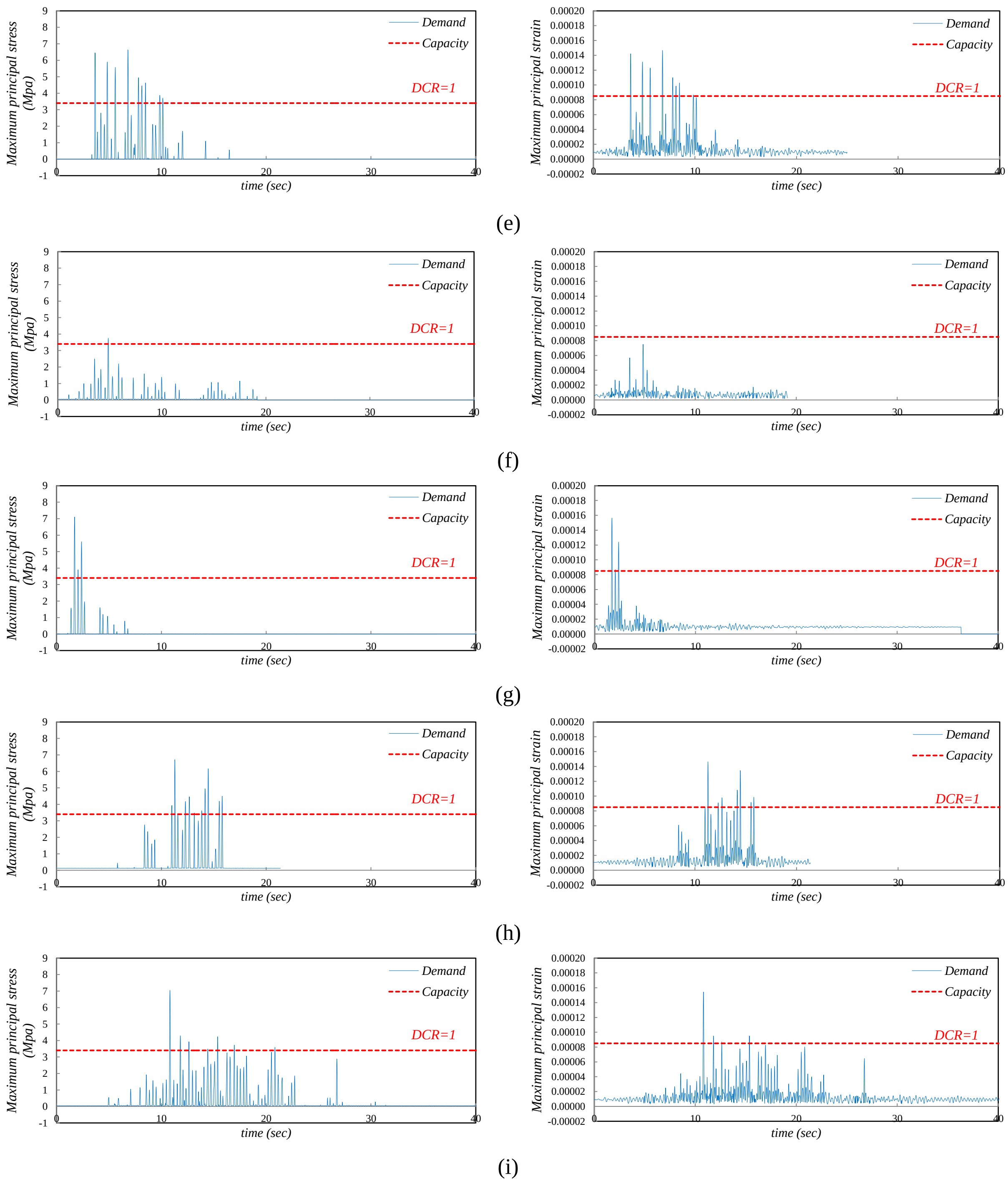


Fig. 3. Time-history of first principal stress and strain for the most critical node in dam (a) No.1, (b) No.2, (c) No.3, (d) No.4, (e) No.5, (f) No.6, (g) No.7, (h) No.8, (i) No.9.

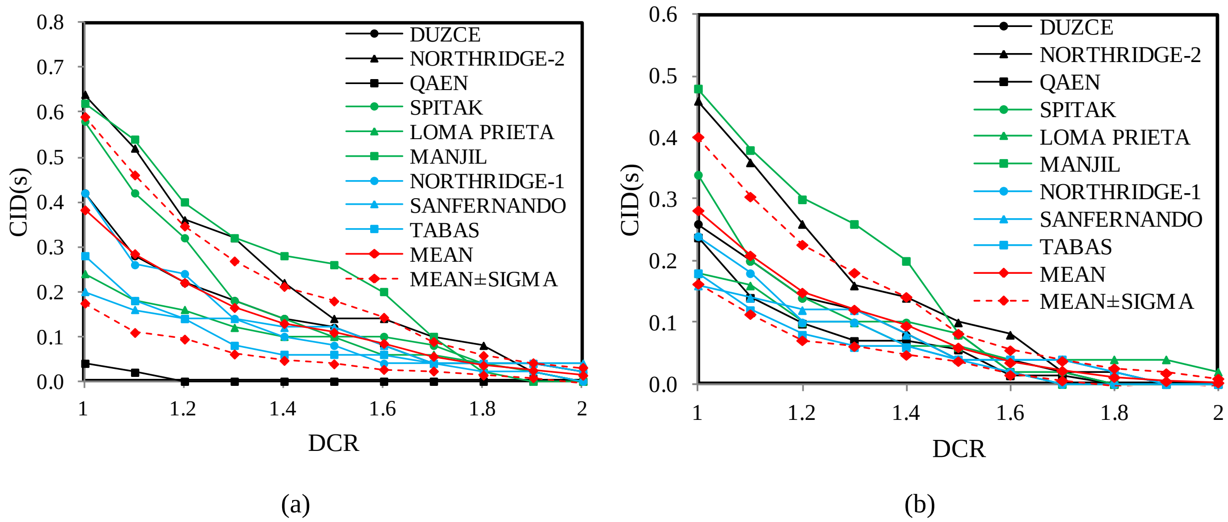


Fig. 4. Performance curves in term of CID-DCR for critical nodes in the dam,
(a) stress-based approach, (b) strain-based approach.

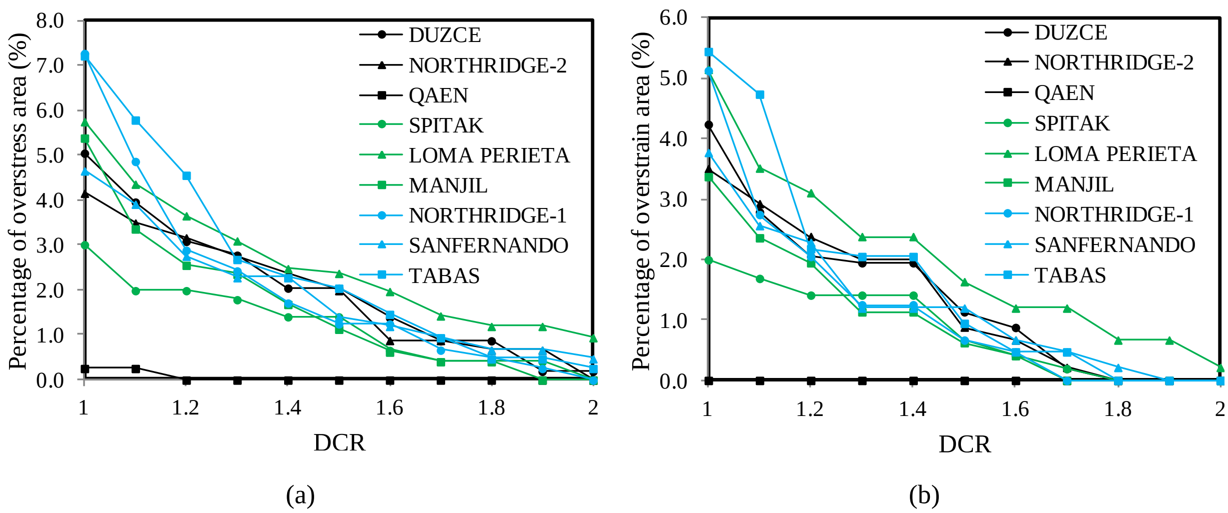


Fig. 5. Percentage of
(a) overstressed, (b) overstrained areas on the upstream face of the dam body.

CONCLUSIONS

As previously mentioned, all the guides and criteria for structural performance assessment of concrete arch dams in the literature are based on the stress. However, the behavior of mass concrete is governed by the strain. In the present paper, the seismic performance assessment of concrete arch dams was considered using criteria based on both the stress and the strain. For this purpose Dez Dam, which is a high double curvature arch dam, was selected and the numerical model of the dam-reservoir-foundation was constructed using the finite element technique. Nine earthquake records selected and scaled using the site response spectra in the DBE. Based on the conducted linear analyses, it was found that in spite of some similarities between the results obtained from the stress- and strain-based approaches; there are considerable differences in interpretation of the results. Interpreting the results using the stress-based criteria can lead to different decision making in dams' safety related projects.

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