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SEISMIC CRACKING OF GRAVITY DAMS: MODELLING CONCRETE TENSILE STRENGTH STRAIN RATE EFFECTS

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Abstract

The seismic cracking of concrete dams is controlled by the dynamic tensile strength, $f_{t,dyn}$, that could be mobilized. Strain rate effects ($\dot{\varepsilon}$) are well known to induce an increase in static concrete tensile strength. For simplicity, dam safety guidelines recommend applying a constant dynamic amplification (or impact) factor (DIF) most often taken as 1.5. A constant DIF ignores the influence of the predominant frequency content of ground motions, the dam dynamic characteristics, and the transient magnitude of strain rate effects. In reality, the DIF exhibits transient behaviour and is not constant during an earthquake leading to a DIF ($\dot{\varepsilon}$) which is strain rate dependent. Therefore, while using finite element simulations, it is important to study the transient effects of DIF ($\dot{\varepsilon}$) on dam seismic cracking initiation and propagation (i) to assess the incidence of using a constant DIF, and (ii) to formulate recommendations to improve existing dam safety guidelines. This paper investigates numerical modelling and simulations of seismic cracking of gravity dams considering the transient nature of DIF ($\dot{\varepsilon}$) on $f_{t,dyn}$. After a brief literature review on strain rate effects, the concrete "Continuous Surface Cap Model", available in the computer program LS-Dyna, is validated at the material scale to reproduce strain rate effects from laboratory test data on small concrete specimens published in the literature. Applications of seismic cracking assessments are then performed on a 78 m typical gravity dam located in North America for low frequency (2Hz) and high frequency (10Hz) ground motion records. Incremental finite nonlinear seismic cracking analyses of the dam are performed while increasing the ground motions PGA. It is shown that a constant DIF of 1.5 is globally adequate for low frequency earthquake (2Hz) and slightly conservative for high frequency motion (10Hz) where DIF $\cong$ 1.8. More importantly, it is also shown that a rigorous consideration of transient strain rate effects could alter significantly the computed crack patterns, and related potential failure mechanisms (crack spatial localization and penetration), favoring damage concentration in the upper crest block.

Keywords: concrete dams, cracking, tensile strength, strain rate effects, nonlinear finite element analyses

1. Introduction

The seismic structural analyses of concrete dams usually follows a progressive approach of increasing complexity including (i) response spectra analysis (RSA), (ii) linear time history analysis (LTHA), followed by (iii) nonlinear time history analysis (NLTHA), if need be. Concrete cracking is allowed under earthquakes loads. However, the structural stability of cracked components must demonstrated during and after ground motions such that water retention capability of the dam is not compromised. The dynamic tensile strength of mass concrete, $f_{t,dyn,}$ is playing a key role in the assessment of (i) crack initiation, and (ii) subsequent crack propagation forming crack patterns to be investigated for stability. In LTHA, the ratio of induced concrete tensile stress (the demand) is divided by the tensile strength (the capacity) to compute demand capacity ratios, (DCR), representing potential structural damage. In NLTHA, concrete smeared crack model constitutive models are often used as a robust predictor of crack patterns [1]. This is ideally followed by a discrete crack model using gap-friction elements inserted at the boundaries of crack components to compute displacement and assess stability. Seismic loads induce tensile concrete strain rate for which the tensile strength is known to increase significantly as compared to its static value, $f_{t,sta}$ according to a dynamic amplification (impact) factor (DIF) defined as $f_{t,dyn}$ / $f_{t,sta}$. This increase varies depending on the strain rate applied. Therefore, strain rate effects on tensile strength should ideally be considered when assessing seismic behaviour of concrete structures, irrespective of the structural analysis method used (RSA, LTHA, NLTHA). For simplicity, dam safety guidelines recommend applying a constant DIF, most often taken as a constant value of 1.5 [2-3]. A constant DIF ignores (i) the influence of the predominant frequency content of ground motions, (ii) the dam dynamic characteristics, and (iii) the transient magnitude and spatial distribution of strain rate effects. In reality, the DIF is not constant during an earthquake leading to a DIF ($\dot{\varepsilon}$) dependent on strain rate. Previous research studies on seismic cracking of gravity dams taking into account strain rate effects on tensile strength [4-6] have concluded that using DIF ($\dot{\varepsilon}$) can alter significantly the computed crack patterns. Now days, concrete constitutive models including strain rate effects are available in commercial finite element codes such as ABAQUS [7] and LS-Dyna [8], allowing to consider strain rate effects in dam engineering industrial applications. However, this require the a priori validation of the available strain rate model. It is then possible (i) to investigate the incidence of using the more rigorous DIF ($\dot{\varepsilon}$), instead of DIF = 1.5, as well as (ii) the incidence of the frequency content of the earthquake records on the related computed crack patterns.

To meet the stated objectives, this paper first presents a brief overview of DIFs obtained from experimental data in the literature. The adequacy of the nonlinear concrete strain rate model available in the computer program LS-Dyna is then investigated at material scale, reproducing published experimental data. Finally, strain rate effects are investigated from the seismic responses of a 78m high gravity dams using (i) LTHA with DIF =1.0 and 1.5, and then NLTHA using DIF = 1.0, 1.5 and DIF ($\dot{\varepsilon}$). The dam has been subjected to both low frequency ground motions (≅ 2Hz), typical of Western North America (WNA), as well as high frequency ground motions (≅10Hz), typical of Eastern North America (ENA). It is shown that a rigorous consideration of transient strain rate effects could alter significantly the computed crack patterns and related potential failure mechanisms.

2. Strain rate effects on concrete tensile strength

In the case of earthquakes with strain rate of the order of 10^{-3} s^{-1} to 10^{-2} s^{-1}, the concrete tensile strength could be 50% to 100% larger than its static strength. As a result, numerous experimental studies have been conducted to better understand the dynamic tensile behaviour of concrete. Figure 1 presents a synthesis of results that we compiled from several experimental studies on concrete dynamic tensile strength [9].

USBR [2] conducted experimental studies on concrete samples taken from 15 different concrete dams (Table 1). For the tested cores, an average 44% increase (DIF = 1.44) was measured for the dynamic tensile strength, with a 15% coefficient of variation. According USBR [2], it would be preferable to test each dam independently from the others, because the results show some variability. Raphael [10] achieved an average increase of 66% (DIF=1.66) for tensile strength from laboratory tests. Darbar et al. [11] conducted dynamic tests on core samples extracted from Ruskin Dam in British Columbia applying cyclic loading of increasing intensity over time instead of a single shock, as often done. They observed 22% increase in tensile strength for bulk mass concrete. For weaker lift joints, the dynamic increase was 36%. These values are smaller than DIF=1.5, often used as a rule of thumb, the DIF being reduced by applying a cyclic loading protocol.

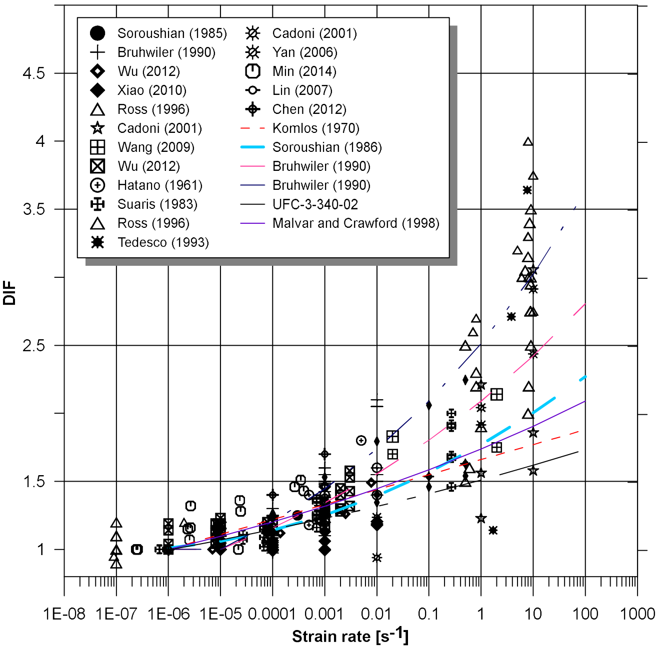

Fig. 1– Dynamic (Impact) Amplification Factor (DIF) of static tensile strength due to strain rate effects [1]

Several empirical relationships have been proposed by different authors to illustrate the increase in tensile strength due to strain rate effects. These relationships are usually logarithmic. Yan et al. [12] and Lin et al. [13] proposed the following relationship following experimental tests on dynamic tensile strength of structural concrete:

$$\mathrm{DIF} = \frac{f_{t\,dyn}}{f_{t\,stat}} = 1 + 0.134\log(\dot{\varepsilon}/\dot{\varepsilon}_s) \tag{1}$$

Where $\dot{\varepsilon}$ corresponds to the strain rate applied to the material and $\dot{\varepsilon}_s$ represents the quasi-static strain rate usually equal to 10^{-5} s^{-1}. Chen et al. [14] relied on cracking and thermodynamic theory to develop an exponential relationship that predicts the sensitivity of concrete to the strain rate effects based on the type of test used. This relationship is:

$$\mathrm{DIF} = \frac{f_{t\,dyn}}{f_{t\,stat}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{0.002\cdot(\mathrm{HSV})^{0.19}} \tag{2}$$

Where HSV represents a parameter that depends on the type of test and the size of the specimen. However, results from Table 2 indicates that if the concrete specimens have been subjected to significant static tensile stresses leading to microcracking prior to dynamic loading, the DIF could be substantially reduced as compared to virgin specimens. Parameters that can change the sensitivity of tensile strength to strain rate effects are addressed in the following sections.

3.Modelling strain rate effects at the material scale

The objective of this section is to perform numerical simulations of dynamic tensile tests at the concrete material scale. The results obtained from these numerical tests will be compared with experimental results presented in the literature. These preliminary studies ascertain whether the concrete LS-Dyna MAT_CSCM (Continuous Surface Cap Model), to be used at the dam scale, is performing adequately for the intended purpose. The MAT_CSCM has the particularity of being able to account for strain rate effects in its formulation according to Eqs (3-5) detailed in section 5.

Table 1– Dynamic properties of concrete dam from experimental tests on concrete cores [9]

Reference	Dam	Tensile (MPa)			Compression (MPa)			Young's modulus		
		Stat	Dyn	DIF	Stat	Dyn	DIF	Stat	Dyn	DIF
Raphael (1974)	Crystal Springs	3.37	4.41	**1.31**	31	41	1.32	-	-	-
	Big Tujunga A	-	-	-	24	28	1.15	-	-	-
	Big Tujunga B	-	-	-	37	41	1.12	-	-	-
	Santa Anita	3	4.4	**1.48**	31	41	1.3	-	-	-
	Juncal	3.2	5	**1.56**	30.5	46.5	1.52	-	-	-
	Morris	3.2	4.8	**1.46**	36.5	53.5	1.47	-	-	-
USBR (1999)	Deadwood	3.14	4.76	**1.52**	34.1	40.9	1.20	23.9	26.4	1.10
	Elephant Butte	2.14	3.45	**1.61**	17.4	25.2	1.45	19.0	18.7	0.98
	Monticello	2.31	3.48	**1.51**	32.8	33.6	1.02	39.7	42.2	1.06
	Warm Springs	2.28	3.52	**1.55**	21.2	17.5	0.82	24.7	19.9	0.81
	Hoover	3.90	6.72	**1.73**	49.8	55.4	1.11	45.4	29.9	0.66
	Stewart Mountain	2.34	3.55	**1.51**	34.8	36.9	1.06	26.8	27.5	1.03
	Englebright	4.10	4.03	**0.98**	45	45.9	1.02	32.7	31.9	0.98
	Folsom	3.31	3.52	**1.06**	29.3	32.8	1.12	26.7	23.6	0.88
	Warm Springs	2.31	3.72	**1.61**	26.8	36.4	1.36	20.8	19	0.91
	Roosevelt	3.27	5.20	**1.59**	33.3	31.7	0.95	41.1	17.9	0.84
	Roosevelt	2.90	3.96	**1.37**	29.9	25.7	0.86	44.5	39.3	0.88
	Roosevelt	3.65	5.79	**1.58**	37.2	44.3	1.19	30.7	33.4	1.09
	Roosevelt	4	5.79	**1.45**	42.3	33.4	0.79	42.9	28.3	0.66
Darbar et al. (2016)	Ruskin Dam	1	1.36	**1.36**	37	-	-	39	-	-
Wang, Haibo et al. (2016)	Shapai	1.66-2.05	1.76-2.75	**1.28 1.47**	-	-	-	-	-	-

Table 2– Experimental tests for strain rate effects on DIF (some with pre tensile loadings)[9]

Reference	Type of test	Loading history	w/c ratio	Max. agg. (mm)	Static loading (MPa)	Dynamic loading		Comments
						DIF	$\dot{\varepsilon}$ (s^{-1})	
Wu et al. (2012)	Direct tension	Preloading tension ; - 30%f_t - 50%f_t - 70 %f_t - 100%ft	0.5	20	3.43	$\mathbf{1.46}$ $\mathbf{1.35}$ $\mathbf{1.27}$ $\mathbf{1}$	10^{-3}	Effect of initial loading on the DIF
Min et al. (2014)	Brazilian test	- Monotonic	0.45	40	3.5	$\mathbf{1-0.07\cdot\log(\dot{\varepsilon}_r)}$	$10^{-7}\ a\ 10^{-3}$	Mass concrete
Chen et al. (2015)	Flexure (Cyclic)	Preloading tension ; - 30%f_t - 50%f_t - 70 %f_t - 100%ft	0.45	150	2.85	$\mathbf{1.17}$ $\mathbf{1.32}$ $\mathbf{1.32}$ $\mathbf{1}$	5	Effect of initial loading on the DIF
Shen et al. (2017)	Biaxial Tension & Compression	- Constant compression -Tension monotonic	0.45	80	-	$\mathbf{1+0.179\cdot\log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)}$	$10^{-5}\ a\ 10^{-2}$	Mass concrete

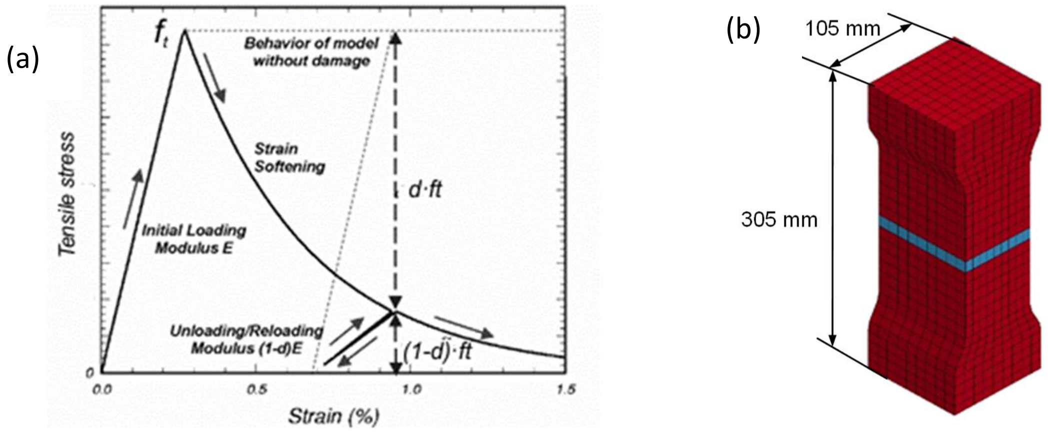

Fig. 2 – Benchmark of LS-Dyna strain rate effects – concrete MAT-CSCM (concrete surface cap model) [8]: (a) tensile constitutive model, (b) concrete FE specimen

To simulate dynamic tensile tests, linearly imposed displacements perpendicular to the top specimen surface are applied (Fig. 2b). For each simulation, the rate of displacement applied is adjusted to achieve the desired strain rate. In this study, the following strain rates were considered: $10^{-4}s^{-1}$, $10^{-3}s^{-1}$, 10^{-2} s^{-1} and $10^{-1}s^{-1}$ (Fig. 3a). The increase in tensile strength, fracture energy, and related DIF ($\dot{\varepsilon}$) obtained from LS-Dyna are quite similar to results obtained experimentally by Brühwiler [15] while testing specimens from existing concrete dams (Fig. 3b). The LS-Dyna concrete material model (MAT-CSCM) is therefore capable of adequately modeling the dynamic behaviour in tension of mass concrete including transient strain rate effects.

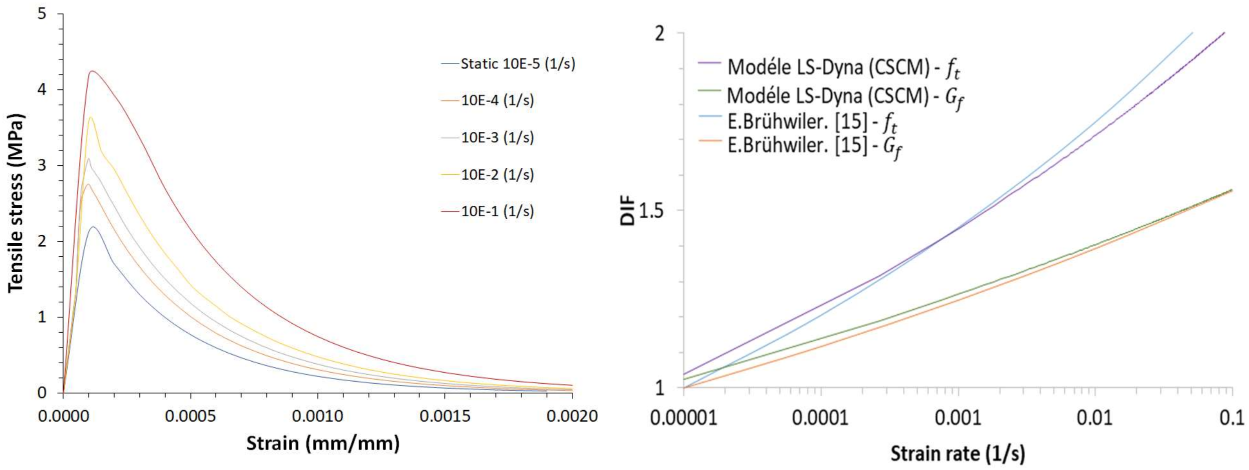

Fig. 3– Benchmark of LS-Dyna strain rate effect [8]: (a) stress-strain response for different strain rates, (b) Computed DIF from LS-Dyna vs Brühwiler experimental data [15]

4. Linear analyses to assess the requirements for nonlinear analyses

Generally, dam safety guidelines require tensile stresses (the demand) to be lower than the tensile strength (the capacity) if concrete cracking is to be avoided. Because nonlinear analyses are difficult to implement, USACE [3] has introduced a systematic approach for the evaluation of the seismic behaviour of concrete dams based on linear time history analysis (LTHA) while recognising cracking significance. This approach provides important information about dam zones likely to experience crack initiation and propagation. The methodology is based on computation of the demand/capacity ratios (DCR). The DCR is defined as the ratio between the maximum allowable tensile stress and concrete tensile strength. Consideration are also given to the cumulative inelastic duration (CID). The CID refers to the total duration of tensile excursions where stresses are above tensile strength. Thereafter, an assessment based on the DCR and CID is applied to estimate the severity of anticipated tensile damage (Fig. 4). If the CID is found below the proposed damage limit threshold for a given DCR, the damage level is considered low to moderate. Then a LTHA is deemed adequate to assess structural safety. Otherwise, damages are considered significant. In this case, NLTHA are required to determine crack patterns as well their incidence on the dam structural performance.

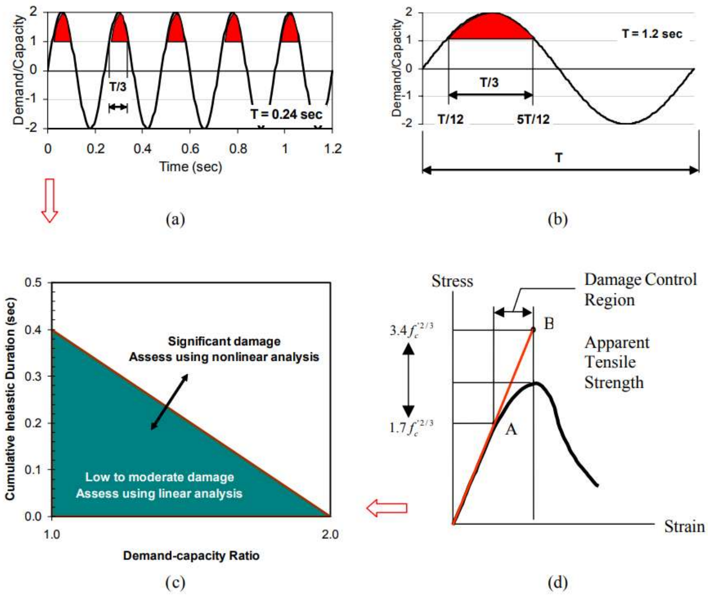

Fig. 4 – USACE [3] procedure to estimate the need for nonlinear seismic (cracking) analysis (NLTHA) from linear analysis (LTHA).

5. Dam-foundation reservoir system analyzed

For this study, an existing gravity dam located in Canada was selected. The dam is made of 19 monoliths with a maximum height of 78 m and a crest length of 300 m. The highest block has been modeled using an elastic modulus E = 32 GPa and 2 % equivalent viscous damping to obtain a fundamental period T_1 = 0.2 s. Figure 5 shows the 3D model of the dam developed with LS-Dyna software. The section of the monolith has a thickness of 14.2 m. The dam is 61.5 m wide at the base with a 4.6 m crest width. For the boundary conditions, it is assumed that the dam rests on a "rigid" foundation rock block (E_f = 70 GPa). Conditions of symmetry (planar deformations) were imposed on the faces of the model to eliminate lateral motions during the seismic analyses.

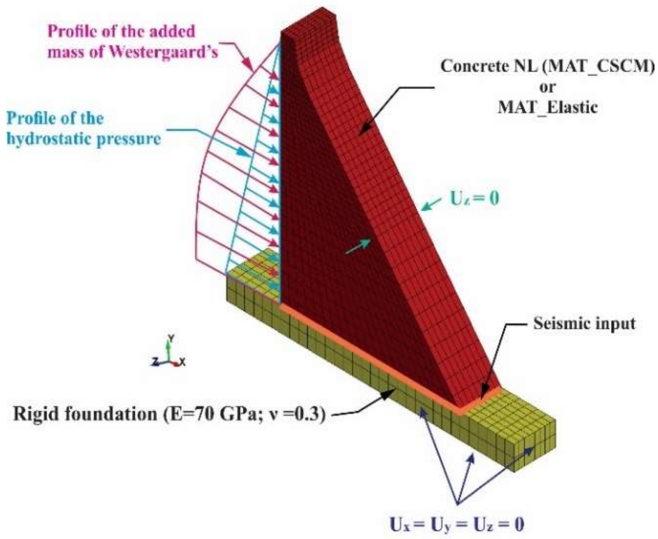

Fig. 5 – 78 m High Dam-reservoir analyzed – LS-Dyna model

Although the dam is located in Eastern North America (ENA), three earthquakes records representative of ENA and Western North America (WNA) seismo-tectonic conditions were selected. This is to study the incidence of ground motion frequency contents on concrete strain rate effects and related dam cracking patterns. One of the ENA record is a synthetic accelerogram (Atkinson 7-A1). Figure 6 illustrates response spectra corresponding to the selected ground motions. For WNA type of records, the maximum spectral acceleration frequencies are close to 2 Hz. For the Imperial Valley and Chi-Chi records, the dominant frequency is 2.5 Hz with maximum spectral accelerations of 1.8g and 0.5g, respectively. For the Northridge earthquake, the maximum spectral acceleration is 1.8g at a frequency of 1.5 Hz. For ENA type of records, the maximum spectral acceleration is occurring at higher frequencies (≅ 10Hz) compared to the WNA records (2Hz). The Atkinson 7-A1 record has a spectral acceleration of 1.9g at a frequency of 10 Hz. For the Nahanni record, the maximum spectral acceleration is 0.6g at a frequency of 13 Hz. Finally, the Saguenay record has a spectral acceleration of 0.35g at a frequency of 10 Hz.

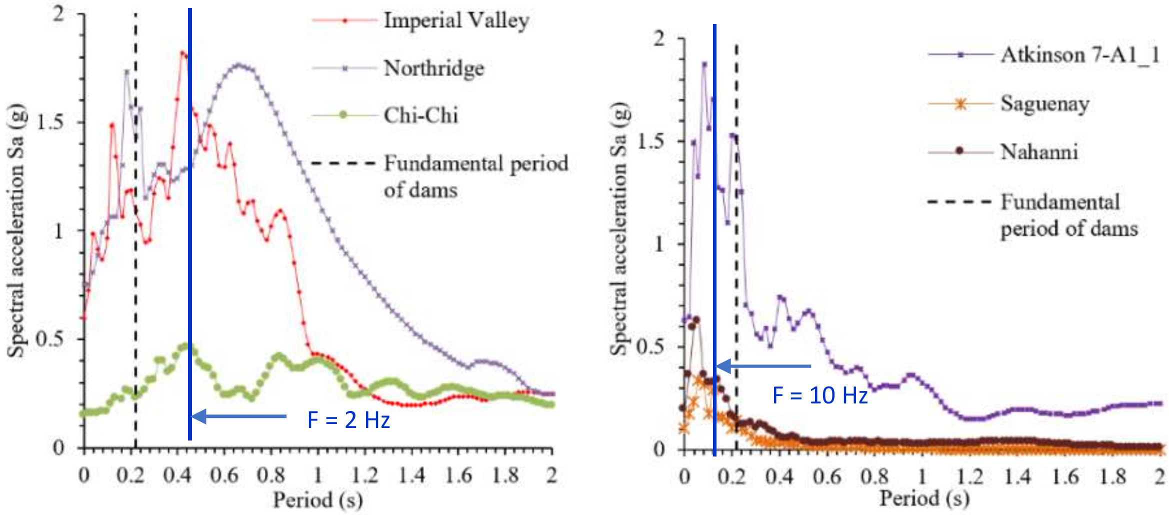

Fig. 6 – Response spectra of accelerograms used in incremental dynamic analyses: (a) Low frequency records (2Hz typical of WNA), (b) High frequency records (10 Hz typical of ENA)

Three different strain rate models were considered during seismic analyses to study strain rate effects on tensile strength. Those were (i) static (DIF=1.0), (ii) dynamic, considering transient strain rate effects (DIF($\dot{\varepsilon}$)), and (iii) dynamic with a constant strain rate effect (DIF=1.5), as recommended in several dam safety guidelines. The mechanical properties of the various concrete materials used in incremental LTHA and NLTHA are presented in Table 3.

For the "static" concrete material, the tensile strength is specified as 2 MPa and the fracture energy is equal to 290 N/m. For "dynamic" concrete, with transient strain rate effects, the tensile strength is equal to (2 MPa) x (DIF_{ft} ($\dot{\varepsilon}$)). The tensile strength is thus a function of the applied strain rate. The relationship between strain rate and dynamic tensile strength used is presented in Eq. 3.

$$f_{t\ dyn}(\text{MPa}) = 2 \cdot \left(\frac{\dot{\varepsilon}}{10^{-5}}\right)^{0.081} \tag{3}$$

Where $\dot{\varepsilon}$ represents the tensile strain rate at the element Gauss points. The fracture energy is equal to (290 N/m) x (DIF_{Gf} ($\dot{\varepsilon}$)). That varies with the rate of strain and this relationship is presented in Eq. 4.

$$G_{f\ dyn}(\text{N/m}) = 290 \cdot \left(\frac{\dot{\varepsilon}}{10^{-5}}\right)^{0.048} \tag{4}$$

Finally, "dynamic" concrete with consideration of constant strain rate effects with DIF_{ft} =1.5 is used for tensile strength, and DIF_{Gf} =1.25 for fracture energy.

Table 3 – Mechanical properties of the concrete strain rate models

Properties	Unit	Nonlinear concrete material (CSCM)		
		Static	Dynamic with strain rate effect	Dynamic without strain rate effect
ρ	kg/m^3	2400	2400	2400
E	GPa	32	32	32
ν	-	0.15	0.15	0.15
f_t	MPa	2	$2\cdot\left(\frac{\dot{\varepsilon}}{10^{-5}}\right)^{0.081}$	2·**1.5**[1]
f_c	MPa	30	30	30
G_f	N/m	290	$290\cdot\left(\frac{\dot{\varepsilon}}{10^{-5}}\right)^{0.048}$	290·**1.25**[2]

1 Recommended value by the USBR [2].
2 The value of DIF = 1.25 is used to major the energy cracking of dynamic models

6. Earthquake response analyses

6.1 Linear time history analyses

The results of LTHA indicates that maximum tensile stresses are mainly concentrated at the base of the dam near the upstream heel, and at the top of the dam for the all ground motion records analysed (Fig.7). For WNA type of records, the magnitude of tensile stresses is largest at the base of the dam at the heel (a point of stress singularity). However, for ENA accelerograms the magnitude of the tensile stresses is higher at the crest. Linear stress time histories are presented in Fig. 8 along with DCR values for different assumptions regarding, the concrete tensile strength. Figure 9 shows the severity of anticipated damage from LTHA.

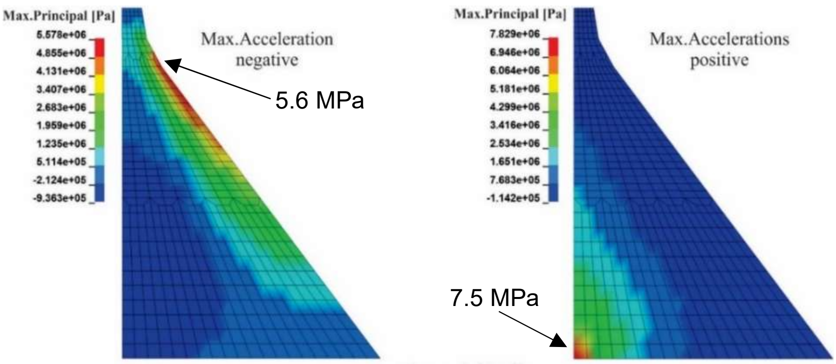

Fig. 7 – Typical envelope of tensile stresses (WNA record scaled at PGA=0.6g)

For WNA records, the level of probable damage is low when the PGA = 0.2g considering that the dynamic tensile strength is equal to 3 MPa (DCR = DIF 1.5, Fig. 9a). However, when the PGA = 0.4g the level of probable damage becomes important even considering the dynamic tensile strength with DIF=DCR=1.5. For ENA records, the level of probable damage is low when the PGA = 0.4g even if dynamic tensile strength is taken as its static value (DCR = DIF = 1.0). In contrast, in the case of the PGA = 0.6g, the level of probable damage is considered severe for all values of DCR=DIF reported and for both type of accelerograms. In short, according to USACE's proposed dam damage assessment method [3], a NLTHA is required for WNA record when the PGA = 0.4g and DIF =1.5. For ENA records a non-linear analysis is required in case the PGA = 0.6g and DIF =1.5. High frequency ENA records have shorter cumulative durations above the specified tensile strength as compared to low frequency WNA records.

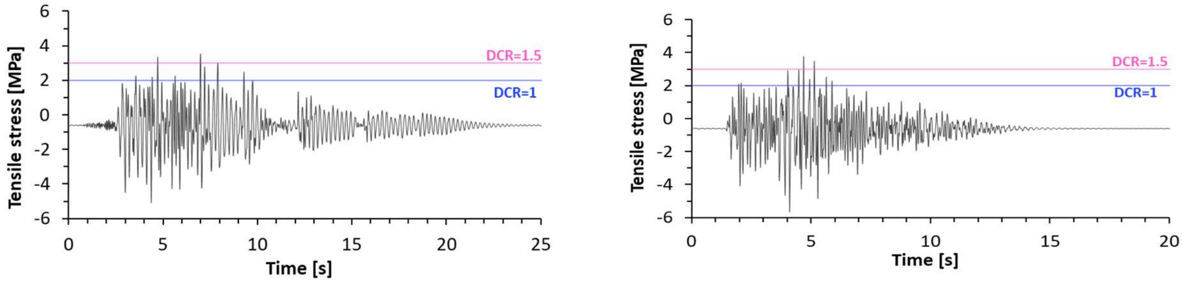

Fig. 8 – Examples of tensile stress time histories vs tensile strength and demand capacity ratio (DCR): (a) Imperial Valley (El Centro) record. (b) Atkinson A1 record

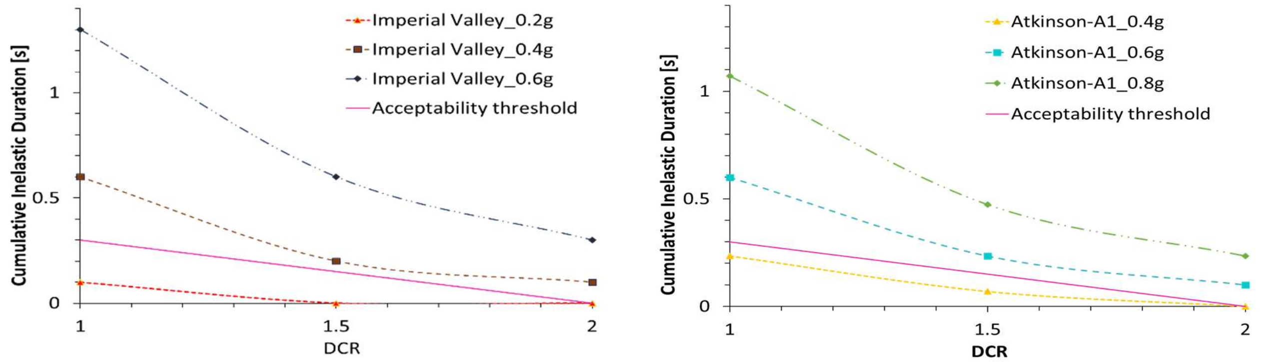

Fig. 9 – Cumulative inelastic duration vs Demand Capacity Ratio for increasing seismic intensity: (a) WNA - Imperial Valley record, (b) ENA - Atkinson record

6.2 Assessing the dynamic strength of concrete (DIF($\dot{\varepsilon}$))

WNA records are characterized by lower frequencies (2 Hz) with relatively long acceleration pulses in the same direction. For WNA records, the average strain rate at the base of the dam is $1{\cdot}10^{-3}$ s^{-1} while in the upper part of the dam, the strain rate is $2{\cdot}10^{-3}$ s^{-1} (Table 4). In addition, for WNA accelerograms, the increase in PGA does not cause a significant change in strain rate and its spatial variability. For ENA accelerograms, the strain rate is more variable in space. The average strain rate at the top ($5.4{\cdot}10^{-2}$ s^{-1}) is larger than the value at the base of the dam ($2{\cdot}10^{-3}$ s^{-1}). This induce a non-uniform distribution of dynamic strength in tension throughout the dam body. In the upper part, the computed DIF is equal to 1.80. In contrast, the DIF at the base of the dam is 1.5. In addition, for these ENA records, the increase in their intensities (PGA) tends to increase the strain rate and dynamic tensile strength of the upper part of the dam, contrary to observations made for WNA records.

6.3 Seismic cracking patterns - transient DIF($\dot{\varepsilon}$) vs DIF = 1.5

A series of non-linear seismic analyses were performed using LS-Dyna with the CSCM material, considering the transient strain rate effect on dynamic tensile strength (DIF ($\dot{\varepsilon}$)) compared to conventional analyses (constant DIF = 1.5). When DIF ($\dot{\varepsilon}$) is used, seismic cracking becomes important when the PGA = 0.6g WNA (Fig. 10a) and the PGA = 0.8g for ENA (not shown). The model with DIF ($\dot{\varepsilon}$) develops larger tensile strengths during maximum acceleration excursions. As a result, DIF ($\dot{\varepsilon}$) reduce crack initiation and propagation through the elements during large stress demand. In contrast, models without transient effect of the strain rate (e.g. DIF=1.5), cracking of the elements occurs earlier because of the significant tensile stresses demand in relation to the tensile strength capacity of the element (Fig. 10b).

Table 4 – Computed DIFs near the crest (slope change) for each earthquake record ($f_{t,sta}$ = 2MPa)

	Earthquake	PGA(g)	f_{tdyn}(MPa)	*DIF*	$\overline{DIF}$	$\dot{\varepsilon}_{failure}$	$\bar{\dot{\varepsilon}}_{failure}$
West	*Northridge*	0.2	-	-	1.56	-	$3.0 \cdot 10^{-3}$
		0.4	3.00	1.50		$1.5 \cdot 10^{-3}$	
		0.6	3.25	1.63		$4.0 \cdot 10^{-3}$	
	Imperial Valley	0.2	-	-	1.51	-	$2.0 \cdot 10^{-3}$
		0.4	2.80	1.40		$1 \cdot 10^{-3}$	
		0.6	3.23	1.62		$4.0 \cdot 10^{-3}$	
	Chi_Chi	0.4	-	-	1.54	-	$2.0 \cdot 10^{-3}$
		0.6	2.95	1.48		$1.0 \cdot 10^{-3}$	
		0.8	3.10	1.55		$2.0 \cdot 10^{-3}$	
		1	3.2	1.60		$3.0 \cdot 10^{-3}$	
East	Atkinson_1A	0.4	2.65	1.33	1.85	$3.2 \cdot 10^{-4}$	$1.4 \cdot 10^{-1}$
		0.6	3.31	1.66		$5.0 \cdot 10^{-3}$	
		0.8	4.00	2.00		$5.2 \cdot 10^{-2}$	
		1.0	4.80	2.40		$5.0 \cdot 10^{-1}$	
	Saguenay	0.4	3.00	1.50	1.75	$1.5 \cdot 10^{-3}$	$2.1 \cdot 10^{-2}$
		0.6	3.45	1.73		$8.4 \cdot 10^{-3}$	
		0.8	4.00	2.00		$5.2 \cdot 10^{-2}$	
	Nahanni	0.4	2.75	1.38	1.70	$5.1 \cdot 10^{-4}$	$1.8 \cdot 10^{-3}$
		0.6	3.25	1.63		$4.0 \cdot 10^{-3}$	
		0.8	3.81	1.91		$2.9 \cdot 10^{-2}$	
		1	3.90	1.95		$3.8 \cdot 10^{-2}$	

The cracks for the model with DIF ($\dot{\varepsilon}$) are located only at the heel of the dam, and on the downstream face near the change in slope (Fig. 10a). The cracking patterns of the model with DIF ($\dot{\varepsilon}$) is consistent while increasing the PGA, the same crack patterns are repeated and are propagating more and more. However, for models with constant DIF, the cracking patterns may change of location with an increase in ground motion intensity (Fig. 10b). Including DIF ($\dot{\varepsilon}$) makes a difference in locating areas that are susceptible to cracking. When a zone is subjected to tensile stresses, the crack will initiate (or propagate) where the strain rate is lowest.

The results of rigorous NLTHA are compared with the estimated damages based on the USACE [3] LTHA presented in section 4. The severity of seismic damage estimated from USACE [3] differs from NLTHA with DIF ($\dot{\varepsilon}$). USACE [3] predicted that the damage would be significant when the PGA = 0.4g for WNA records and 0.6g for ENA records. However, for the NLTHA model with DIF ($\dot{\varepsilon}$), damages become important when the PGA = 0.6g for WNA records and 0.8g for ENA records. In contrast, for models using NLTHA with constant DIF (1.5 or1.0), the estimated damage obtained from the USACE [3] approach exhibits consistency when comparing to those obtained from NLTHA with constant DIF (Figs 10b,c).

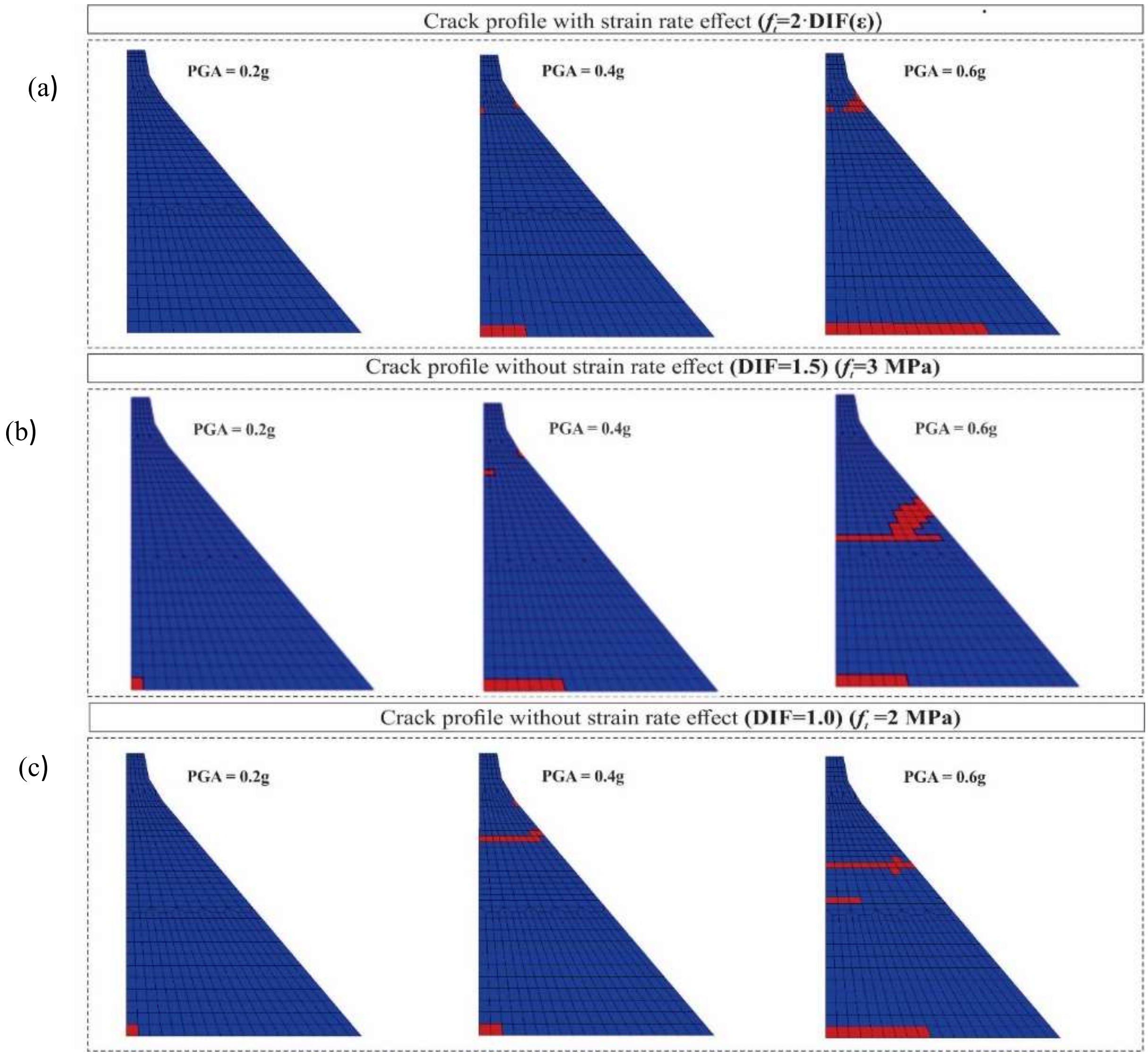

Fig. 10 – Seismic cracking (in red) from incremental dynamic analyses under Imperial valley record; (a) DIF($\dot{\varepsilon}$), (b) DIF=1.5, (c) DIF =1

7. Conclusions

In the safety assessment of concrete dams, tensile strength is the predominant parameter controlling crack initiation and propagation during earthquakes. Currently, it is widely accepted in the literature, and dam safety guidelines, that concrete tensile strength is sensitive to strain rate. Studies were conducted herein to evaluate the LS-Dyna Continuous Surface Cap Model (CSCM) material through numerical simulations (tensile tests) at the material scale. It was shown that CSCM is able to reproduce the dynamic amplification (impact) factor (DIF($\dot{\varepsilon}$)) with transient strain rate effects on tensile strength, and fracture energy, as reported in the literature for mass concrete.

The seismic cracking analysis of a 78m high gravity dam was then studied using linear time history analyses (LTHA) with constant DIF=1.5, and nonlinear time history analyses, NLTHA, with either constant DIF=1.5 or transient strain rate effects (DIF($\dot{\varepsilon}$)). The initiation and propagation of cracks obtained using (DIF($\dot{\varepsilon}$)) is different from the conventional approach with DIF = 1.5. The transient strain rate model is able to predicts crack initiation (localization) with minimal diffusion of crack patterns with increasing earthquake record intensity. Seismic cracking, when considering (DIF($\dot{\varepsilon}$)), is less severe as compared to using DIF = 1.5. For the DIF($\dot{\varepsilon}$) model, cracking becomes severe (detached crest block) when the PGA reaches 0.6g for WNA records and 1.0g for ENA records. On the other hand, for models with DIF = 1.5 severe cracking occurs also when the PGA is 0.6g for WNA records, but with a through crack much lower in the dam body than before. However, for ENA records a detached crest block is observed for PGA=0.6g. It is therefore recommended to perform sensitivity analyses, ideally considering a constitutive model with transient strain rate effects, to assess the variability of computed crack patterns from smeared crack model to be used in stability assessment using gap-friction element inserted along cracks.

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