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TITLE

Effect Of Seismic Motion Variability On Damage Sustained By RC Structures

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SUMMARY

Since earthquake prediction still remains impossible, foreseeing damages experienced by a structure submitted to a seismic event has become a key point in earthquake engineering. This work aims at evaluating the relevance of classical seismic signal damaging potential indices and at proposing improvement of these indices in order to provide better prediction of structural damage due to earthquakes.
It first supplies a non exhaustive state of the art of main Damaging Potential Indices I_P and Damage Indices I_D used in earthquake engineering. I_P/I_D correlations results are analysed in order to evaluate I_P relevance, to justify displacement based approach use (capacity spectrum method) for damage prediction and to make good the proposal for improvement of Damaging Potential Indices.
It appears first that the most relevant "elementary" I_P in the studied cases are Destructive Power and Spectral Intensity and secondly that this relevance can be improved by combining cumulative and "threshold" I_P into "complex" I_P: to combine cumulative I_P such as Cumulative Absolute Velocity (CAV) or Arias Intensity with "threshold" I_P such as Peak Ground Acceleration (PGA) leads to divide damage scatter by at least 2 and then increases the determination factor by more than 15%. Moreover, displacement based approach using non linear static analysis and Capacity-Spectrum Method (CSM), does not generate much more uncertainties on damage than classical non linear time history analysis. This result justifies CSM use all the more because simplicity of this method encourages parametric studies.

INTRODUCTION

Building damage measurement during and after an earthquake remains an economical as well as technical stake as difficult to cope with as the problem it raises all the more because its importance depends on the field or the function of the building: civil, medical, military, nuclear… Even building ruin remains one of the most critical diagnosis to establish. Then since prediction of earthquake still remains impossible, foreseeing structural damages due to seismic motion has become a key point in earthquake engineering.
This work aims at evaluating the relevance of classical seismic signal damaging potential indices and at proposing improvement of these indices in order to provide better prediction of structural damage due to earthquake.
The first part supplies a non exhaustive state of the art of main Damaging Potential Indices I_P and Damage Indices I_D used in earthquake engineering. The second part provides assumptions for modelling and

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calculations. In the third part, I_P/I_D correlations results are analysed in order to evaluate I_P relevance, to justify displacement based approach use (capacity spectrum method) for damage prediction and to make good the proposal for improvement of Damaging Potential Index.

INTRODUCTION TO DAMAGING POTENTIAL/DAMAGE DIALECTICS

From Seismic Motion Characterization To Damaging Potential Index Calculation

It is a well known fact that damages depend both the nature of earthquake and the structure characteristics. Characterization of seismic motion usually involves a signal representation definition such as simple accelerogram or famous Acceleration Displacement Response Spectrum. From these representations searchers and engineers go on trying to define the damaging potential of an earthquake by performing calculations of what is called Damaging Potential Index (I_P). In the same way, engineers have defined Damage Index (I_D) to describe or quantify structure damages during or after an earthquake. To prove Damaging Potential Index relevance, correlation between I_P and I_D are required. For an accurate Damage Index I_D (representative of real structural behaviour and damage), a small scattering of I_P/I_D correlation a priori corresponds to a relevant Damaging Potential Index.

This first part supplies a non exhaustive state of the art of main I_P and I_D Index used in earthquake engineering.

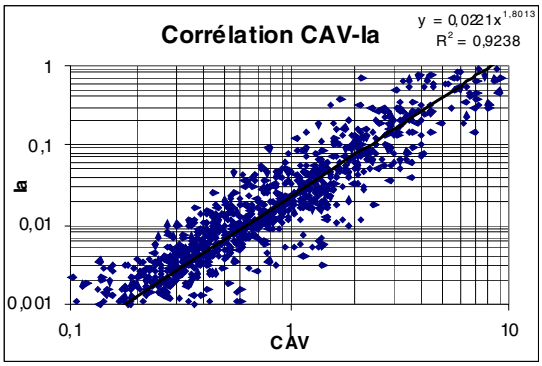
Damaging Potential Index Definition Recall

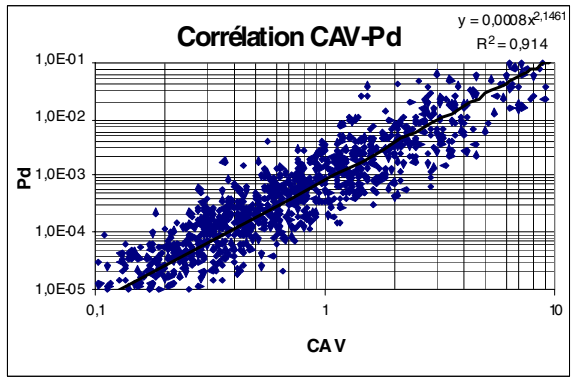
Damaging Potential Index (I_P) of an earthquake commonly is a scalar representation of its ability to damage structures usually derived from seismic event digital signal processing. Damaging Potential Index historical and technical background used in earthquake engineering are precisely described in reference [1], [2]. The actual study has used the following I_P:

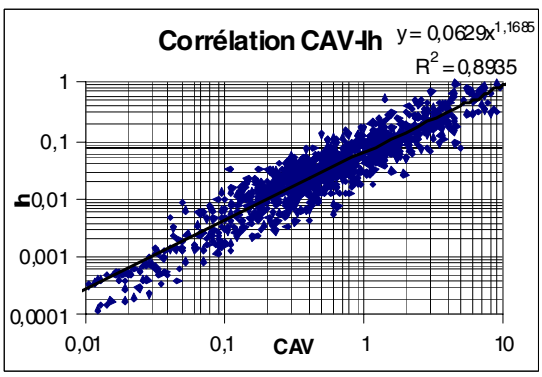
- Maximum Ground Acceleration or Peak Ground Acceleration of earthquake signal: PGA
- Arias Intensity (1970) (I_A or Ia), proportional to energy for a given direction per mass unit injected in the whole of structures whose natural pulsation is between 0 and infinite: $I_A = \frac{\pi}{2g}\int_0^{\infty} a^2(t)dt$ where a(t) represents seismic signal acceleration
- Spectral Intensity (G.W. Housner 1952) performed from pseudo velocity spectra for a given damping: $I_H = \int_{0.1}^{2.5} S_v(T,\xi)dT$ or $I_H = \int_{0.4}^{10} \frac{S_v(f,\xi)}{f^2}df$, where importance of low frequency clearly appears in cumulative energy calculation; frequency band 0.4Hz-10Hz represents civil engineering main natural frequencies domain.
- Cumulative Absolute Velocity: $CAV = \int_0^{t_f} |a(t)|dt$, where t_f represents strong phase duration shaking which can be computed as duration "T" between times corresponding to fraction of "global" CAV (computed on global signal duration) such as 5% to 95%.
- Destructive Power (Sargoni 1981): $P_d = \frac{I_A}{f_d^{\,c}}$, where I_A is Arias Itensity, f_d is signal central frequency, and c is a parameter determined from a statisitcal analysis on acceleration hazard processes equals 2.

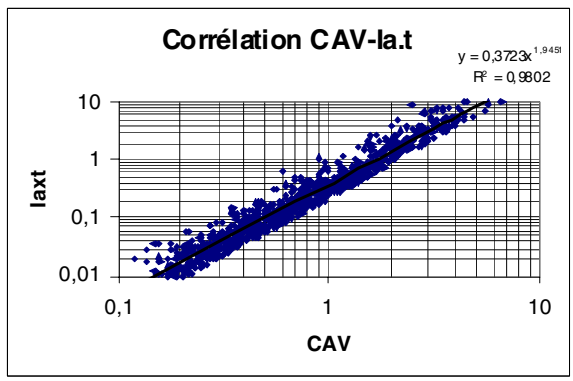
These Damaging Potential Index have been computed for European Strong Motion Database [4] consisted of about one thousand motions for direction x, y and z. Only x direction has been used to performe calculations. Following figures brings up elementary correlations differnet I_P. They provide I_P statistical

repartition of the whole database. Correlation mean curves are obviously rising curves but the scattering red on diagrams excludes simultaneous relevance of two different Damaging Potential Index. Arias Intensity corresponding to a fixed value of CAV can be defined to within a ten factor. Other correlations have been performed with other I_P such as Spectral Intensity I_H or Destructive Power P_d and display high scatterings up to a twenty factor between CAV and P_d.









In order to evaluate I_P relevance, correlations between Damaging Potential (I_P) and Damage Index (I_D) have to be performed.

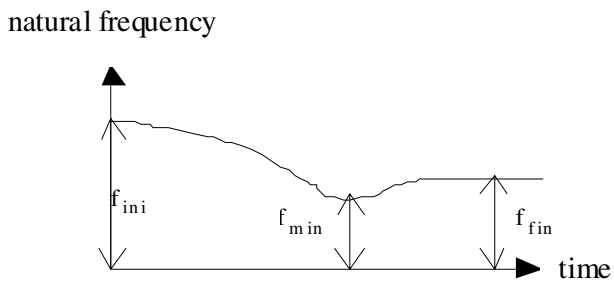
Damage Index Definition Recall

Structural retrofitting in earthquake engineering is a basic question which engineers have more and more to cope with, firstly because of still existing constructions built before seismic rules writing and secondly because even some more recent buildings are ageing. To order retrofitting process priority, seismic hazard assessment referring to a building or facility has to be related to its hypothetic damage consequences. This approach is generally based on a damage probability assessment applied to decision making process which requires structural (or economical) damage index (I_D) definition.

This part supplies some damage Index definition among those currently used in earthquake engineering for reinforced concrete structures [3], [5], [6]. Damage Index used hereafter are differentiated depending on their local or global, cumulative or non cumulative aspect.

Global Damage Index

- Maximum top displacement of the structure: D_{max} or δ_m, considered as a relevant I_D, and used in any displacement based design approach
- Plastic, maximum and final softening: D_{PL}, D_M, D_F, which assumes that structural natural frequency variations reflect structural damage evolution



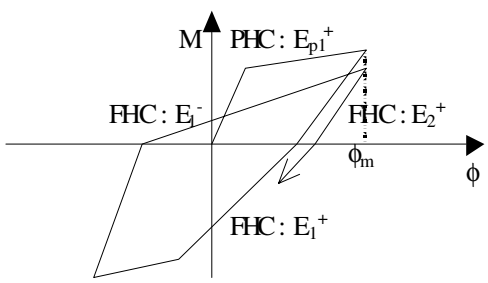
$$D_m = 1 - \frac{f_{\min}}{f_{ini}}$$

$$D_{pl} = 1 - \frac{f_{\min}^{\ 2}}{f_{fin}^{\ 2}}$$

$$D_F = 1 - \frac{f_{fin}^{\ 2}}{f_{ini}^{\ 2}}$$

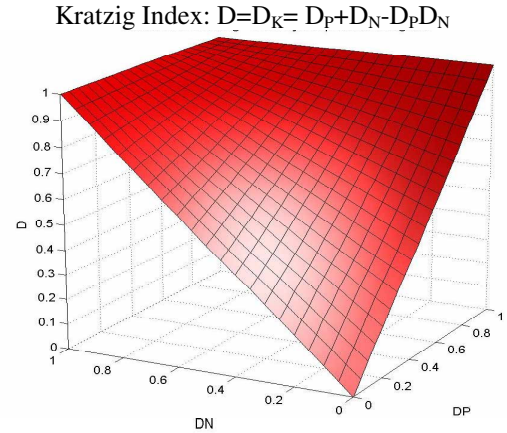
Local Damage Index

- Displacement ductility defined by $\mu_\delta = \frac{\delta_m}{\delta_y} = 1 + \frac{\delta_m - \delta_y}{\delta_y}$ where δ_m and δ_y represent maximum top and elastic displacements (non cumulative I_D)
- Kratzig Index [5] (cumulative I_D) defined by $D_K = D_P + D_N - D_P D_N$ (D_P also noted D_+) from moment curvature cycles (M-ϕ) and illustrated by graphs bellow



$$D^+ = \frac{\sum E_{p,i}^{\ +} + \sum E_i^{\ +}}{E_f^{\ +} + \sum E_i^{\ +}}$$

Kratzig Index: $D = D_K = D_P + D_N - D_P D_N$



MODELING AND CALCULATIONS

Modeling

Damage Index described above have been computed for two different structures :

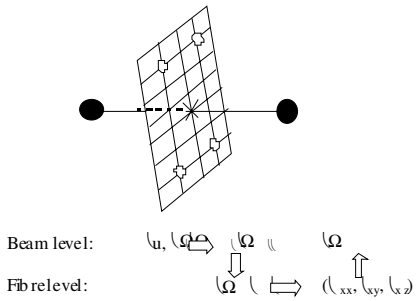
- a simple RC column
- a two storeys RC frame

For both structures, the same finite element and material constitutive laws have been used.

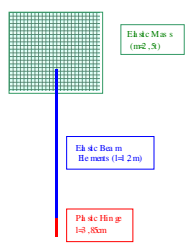
Finite Element Modeling

The numerical analysis have been performed using the general purpose finite element software CASTEM 2000 developped by CEA (Commissariat à l'énergie atomique).

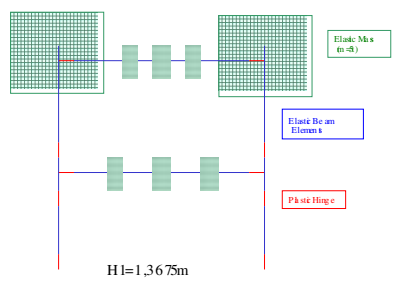
Non linear inelastic behaviour was assumed only for frame nodes and at tops and bases of columns. Finite elements are based on a fibre beam model according to Timonshenko theory [10]. Integration schemes are summed up in the picture bellow:



Finite element mesh for each structure is presented with their fundamental modal characterisitcs here after:



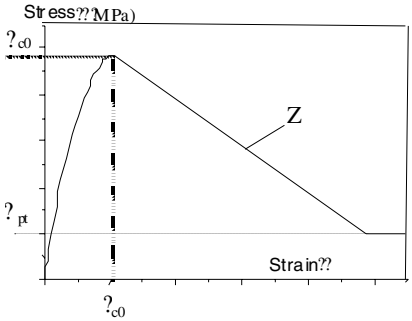
H=1,2385m
M=2,5t
S=13,5cmx13,5cm
A=2Ø8+4Ø6
f1=3,47Hz (80%)
f2=17Hz (≈20%)

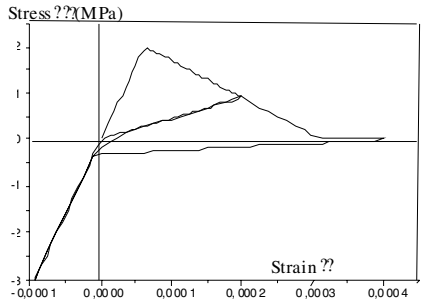


H1=1,3675m
M1=3x0,5t
H2=1m
M2=2x5t+3x1t
M=15t
Scolu=13,5cmx13,5cm
Sbeam=13,5cmx23,5cm
f1=2,71Hz (>95%)
f2=8,95Hz

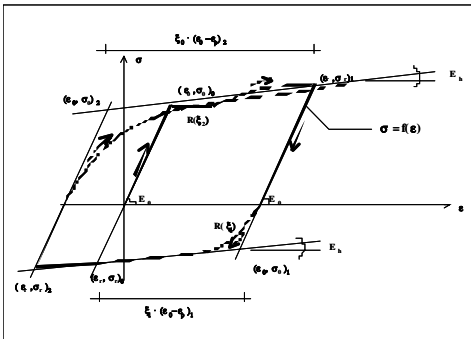
Material constitutuve models

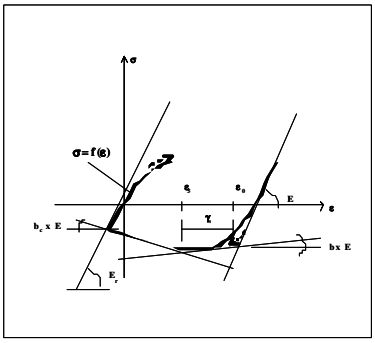
Concrete model, adopts the concept of a smeared crack approach with a possible double cracking only at 90°. It is based upon the plasticity theory for uncracked concrete with isotropic hardening and associated flow rule. Two distinct criteria describe the failure surface: Nadai in compression and bi-compression and Rankine in tension. Hardening is isotropic and an associated flow rule is used. When the ultimate surface is reached in tension, a crack is created perpendicularly to the principal direction of maximum tensile stress, and its orientation is considered as fixed subsequently. Each direction is then processed independently by a cyclic uniaxial law, and the stress tensor in the local co-ordinate system defined by the direction of the cracks. The uniaxial law is displayed by the graphs hera after.





As for steel, a cyclic model which can take into account Bauschinger effect and buckling of reinforcing bars has been adopted. The monotonic branch is characterised by an initial linear branch followed by a plateau and hardening up to failure. The cyclic behaviour is described by the formulation proposed by Giuffré and Pinto and implemented by Menegoto and Pinto in 1973. The steel model is presented on the following graphs.

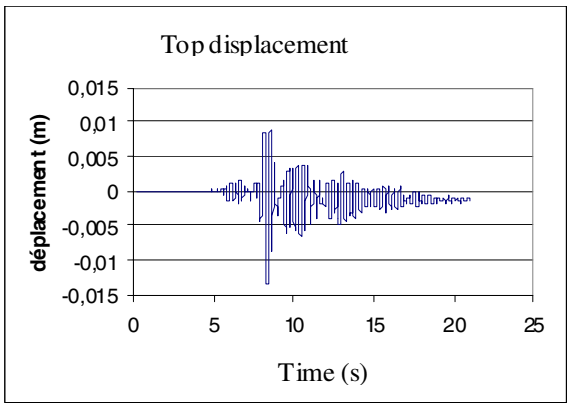


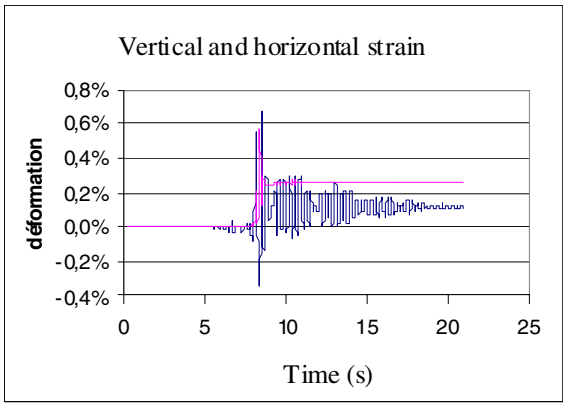


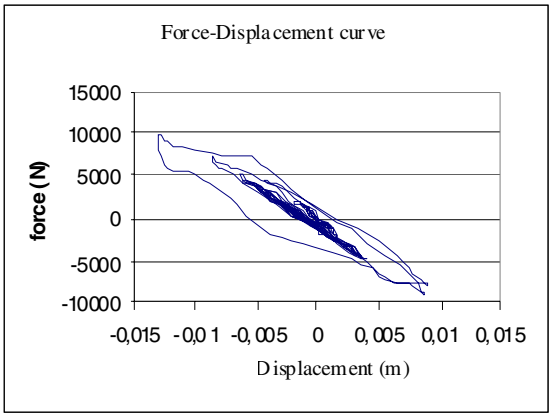
Calculations

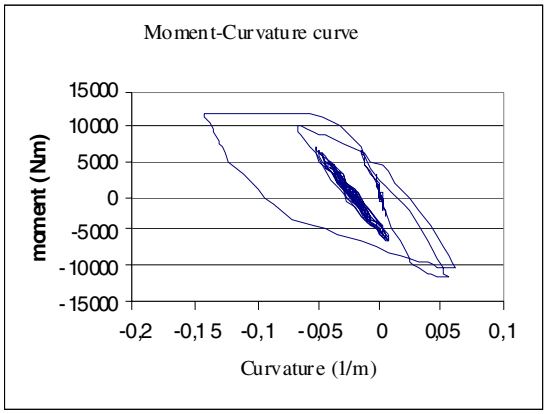
Non linear time history analysis

One hundred time history analysis have been performed for both structures and two Pushover analysis were used to apply displacement based approach (non linear equivalent static method), for which only Maximum Top Displacement was post processed. Graphs bellow illustrate different kind of results before I_D computation.



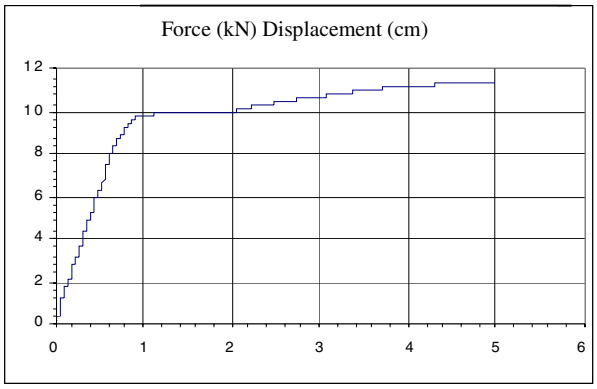


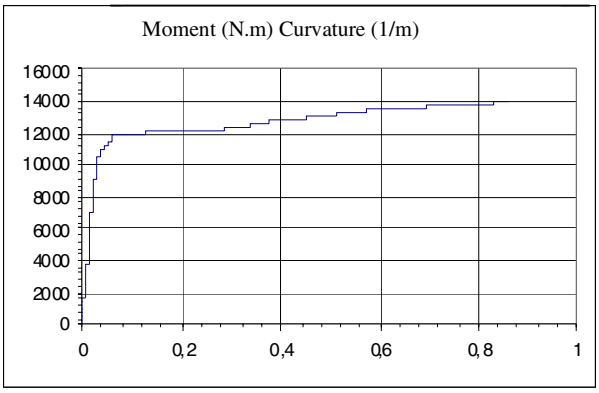




Pusover analysis

Result of column non linear static analysis is represented by graphs below





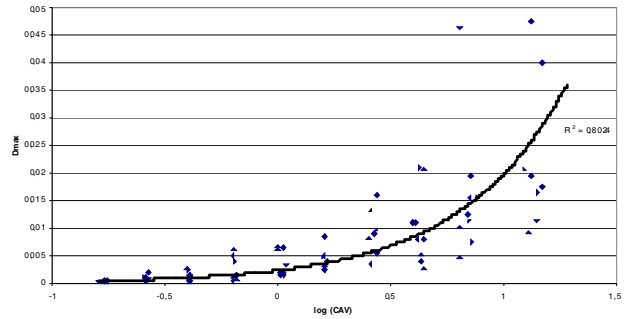
From these results, Damage Index were calculated and correlated to Damaging Potential Index I_P mentioned above in order to evaluate their respective relevance and make a proposal to improve it.

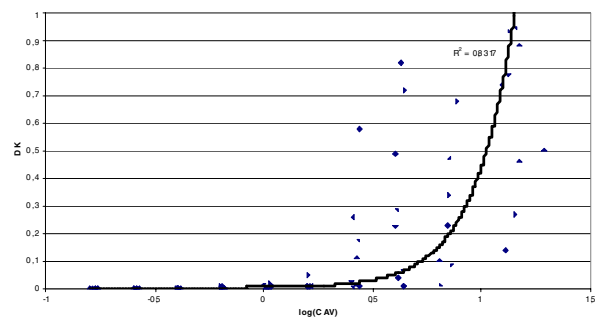
RESULTS AND ANALYSIS: PROPOSAL FOR DAMAGING POTENTIAL INDEX IMPROVEMENT

I_P/I_D correlations have been performed in order to evaluate effects of seismic motion variability on damage scattering for both frame and column described above. The analysis has proceeded to "cliff edge effect" on damage and damage scattering factor research for each damaging potential Index (I_P). Correlations have been performed using damage Index results from two different calculation methods. I_P/I_D correlations from time histories analysis are compared to I_P/I_D correlations from non linear static equivalent method based on ATC 40 approach [7] in order to evaluate damage uncertainties possible amplification due to simple method using. This part finally propounds new damaging potential Index (I_P) to improve correlations and to make it more relevant for structural damage prediction.

“Cliff edge effect” and scattering factor

Correlations between logarithmic I_P (logarithmic scale is useful to correctly describe I_P repartition corresponding data base motions) and linear I_D, systematically display an exponential shape, that is to say damage (I_D) rapidly increases from a limit I_P value. Examples supply illustration of this “cliff edge effect” here after.



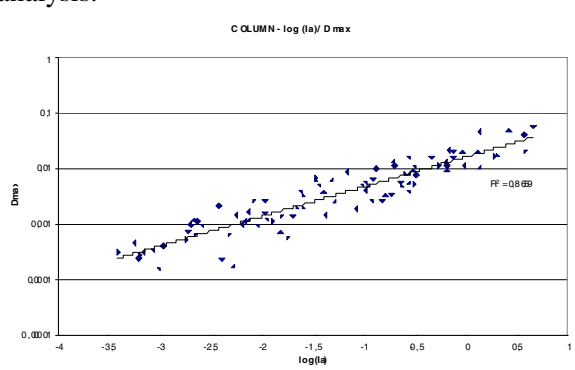


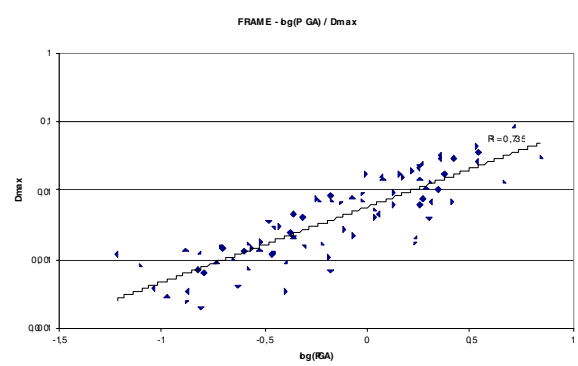
For each I_D, limit the I_P value has been arbitrarily established for a 1.5% $I_D/\log(I_P)$ gradient overstepping. The equations of mean curves correlations defined by $I_D=f(\log(I_P))$ are either $f(x)=ke^{cx}$ type or $f(x)=ax^2+bx+c$ type. Thus, $x_{1.5\%}=\ln(0.015/kc)/c$ or $x_{1.5\%}=(0.015-b)/2a$. The corresponding limit I_P values equal $I_P=10^{x1.5\%}$.

Structural damage uncertainty has been evaluated from scattering factor of I_P/I_D correlations. This scattering is directly estimated on log-log scaled I_P/I_D graphics. With log/log displays, I_P/I_D correlations almost appear linear and corresponding mean curves are straight line. Scattering factor is the determination coefficient R^2 derived from linear regression and represents the I_D variance proportion due to I_P variance. Then R value is given by the following equation:

$$R = \frac{n\left(\sum I_P I_D\right) - \left(\sum I_P\right)\left(\sum I_D\right)}{\sqrt{\left[n\left(\sum I_P{}^2\right) - \left(\sum I_P\right)^2\right]\left[n\left(\sum I_D{}^2\right) - \left(\sum I_D\right)^2\right]}}.$$

Damage scattering of both column and frame versus damaging potential of earthquakes is represented by the following graphs. The following tables summarise this scattering by the determination factor R^2 for each couple (I_P/I_D). The limit I_P value is indicated in brackets. It clearly appears that Damaging Potential Index Destruction Power Pd and Housner Intensity I_H, are the best correlated to the top displacement, D_{max} Damage Index calculated by time history analysis.





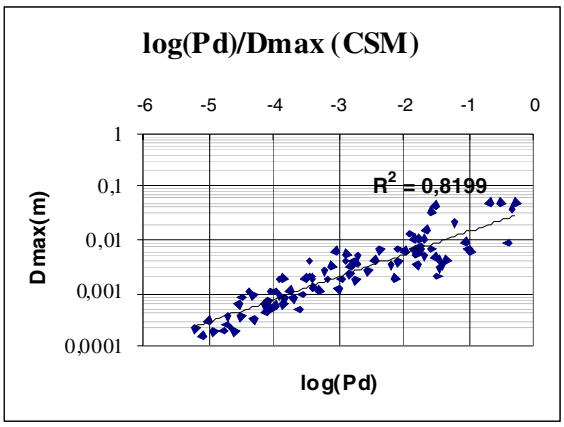
R	I_P	CAV	PGA	Ia	Ia x DUREE	Pd	I_H
I_D	(S)						
Dmax		0 .8024 (3.34)	0.8113 (1.35)	0.8659 (0.57)	0.8237 (16.9)	**0.8579 (0.05)**	**0.8610 (0.29)**
DK		0.8317 (1.15)	0.7581 (0.67)	0.8530 (0.05)	0.8428 (0.95)	0.8459 (2E-3)	0.8526 (7.3E-2)
D_M		0.6244 (0.33)	0.3540 (0.18)	0.5467 (0.05)	0.6289 (0.07)	0.7585 (1.6E-4)	0.6571 (1.3^E-2)

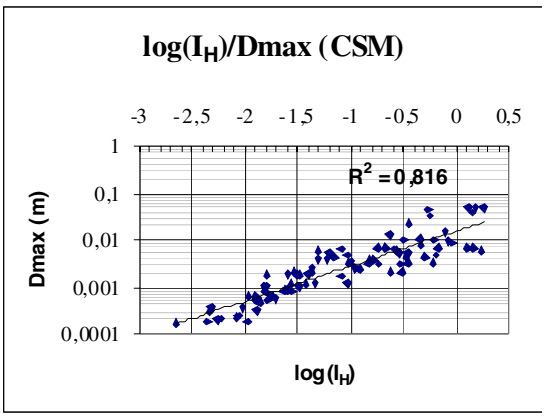
R	I_P	CAV	PGA	Ia	Ia x DUREE	Pd	I_H
I_D	(S)						
Dmax		0.7792 (1.62)	0.7350 (1.02)	0.8077	0.7921 (4.35)	**0.8816 (0.01)**	**0.8974 (0.13)**
D_M		0.5057 (0.33)	0.4933 (0.26)	0.5350	0.5457 (0.06)	0.6835 (1.5E-4)	0.7063 (0.02)

Comparison between Non Linear Static (CSM) and Dynamic Analysis

As mentioned above, the same correlations have been performed by using static non linear equivalent calculation results based on ATC 40 approach (Capacity-Spectrum Method) . This kind of approach provides a performance point which corresponds to the maximum top displacement of the structure. This maximum displacement has been compared to the one obtained by the non linear time history analysis for each previous studied motion.

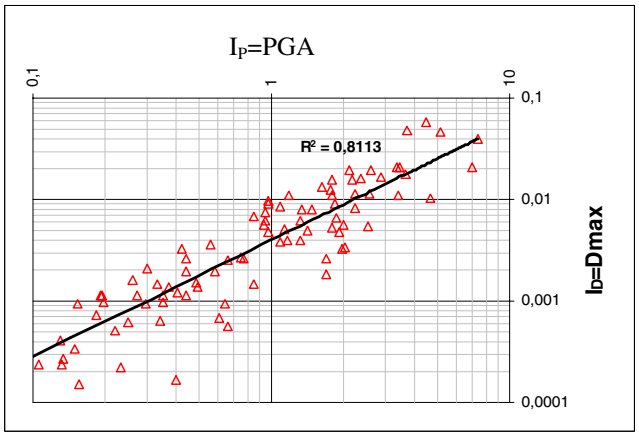
Using Capacity-Spectrum Method (CSM), maximum displacement has been performed and compared with Damaging Potential Index calculated by non linear classical time history analysis. This comparison has underlined that simple approach such as CSM does not generate much more uncertainties on damage than the most sophisticated ones. Scatter factors or R^2 coefficient calculated with simple static and time history Analysis provide comparable results in term of damage uncertainty. The graphs hereafter illustrates this result. This result allows statistical validation of simple displacement static approach and open the way to probabilistic approaches for complex structures including even structural uncertainties.

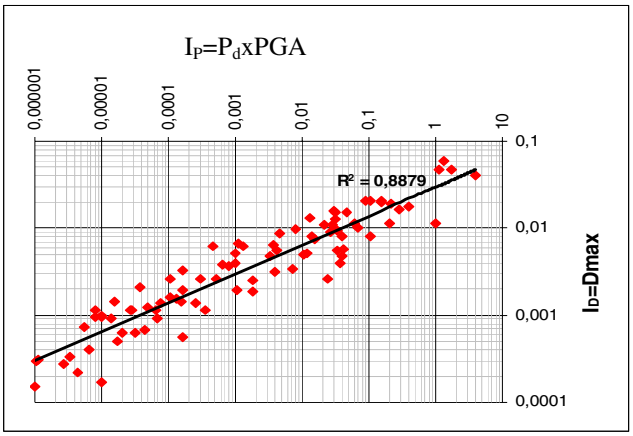


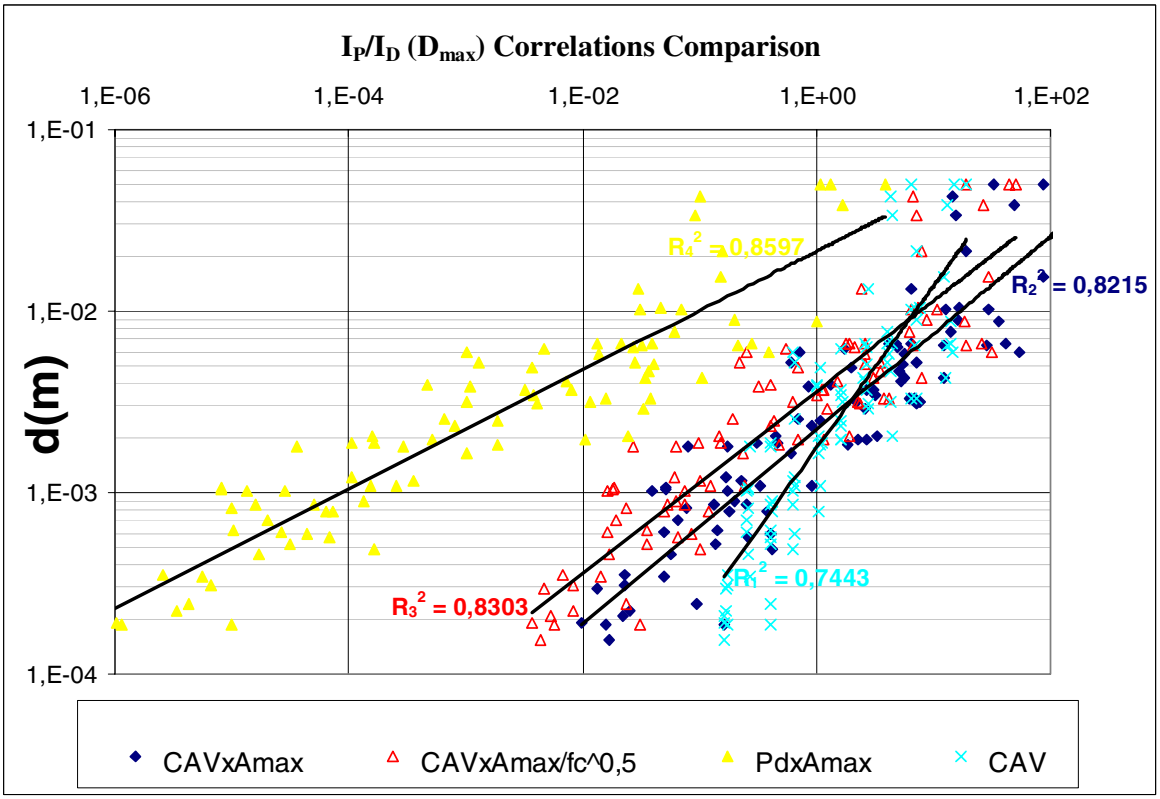


Proposal for improvement of Damaging Potential Index

Up to now "elementary" Damaging Potential Index enable to estimate Damage Index value to within more or less a power of ten. This uncertainty can be largely reduced by using "complex" Damaging Potential Index. In fact, to combine cumulative I_P such as CAV or Ia with "threshold" I_P such as PGA leads to divide damage scatter by at least 2 and then increase the determination factor R^2 by more than 15%. The following graphs show this result by putting forward correlation with "PdxPGA" or "CAVxPGA/fc0.5, where f_c is the central frequency of the signal.







CONCLUSION

(1) The most relevant "elementary" I_P in the studied cases are Pd and I_H.
(2) This relevance can be improved by combining cumulative and "threshold" I_P into "complex" I_P. To combine cumulative IP such as CAV or Ia with "threshold" IP such as PGA leads to divide damage scatter by at least 2 and then increase the determination factor R^2 by more than 15%.
(3) Non linear static analysis, based on Capacity-Spectrum Method [7], does not generate much more uncertainties on damage than classical non linear time history analysis. This result justifies CSM use all the more because simplicity of this method encourages parametric studies.

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