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Division V

QUALIFICATION OF A PRE-DAMAGED PARAMETER FOR RC STRUCTURES UNDER POST-SEISMIC LOADING

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ABSTRACT

RC structures are widely used in nuclear civil engineering. They could be submitted to extreme loading cases such as earthquakes, impacts or explosions. These fast dynamic loadings often have significant consequences on the design of the structure. Moreover, when designing nuclear facilities, engineers may have to consider the consecutive application of two accidental loads. In such a case, the determination of the concrete cracking rate after a first accidental situation is a key parameter in order to estimate the residual strength of the structure when the second occurs.

The purpose of the study is to highlight the accuracy of an equivalent "pre-damage" parameter in comparison with the concrete cracking state obtained after a time-running analysis of a seismic loading.

1. INTRODUCTION AND CONTEXT OF THE STUDY

1.1. Aim of the study

In a first approach, engineers may commonly reduce parameters which impact the Young Modulus, strength and rigidity of concrete by 50% when the cracking state of the element is unknown. The aim of the study is to optimize this ratio introduced in the European standard related to construction of structure under seismic load cases Eurocode 8 [1].

This study only focuses on the case where the first accidental load is a seismic loading. The purpose is to estimate the more accurate value of a pre-damage parameter that can be inputted in the numerical model instead of running a time-based analysis with explicit time-step which is time expensive before applying the second dynamic accidental load which is in this case an explosion.

This study relies on the comparison between two models :

- The first model concerns an explicit time-based calculation of stresses and strains of the structure under accelerations from accelerograms given on §2.1. Once the earthquake will be applied and post-processing calculations will be done, we will apply an explosion loading.
- The second model purpose is then to estimate the accurate value of the pre-damage parameter d to simulate the seismic load case. This will be done by comparison of post explosion results for several values of the pre-damage parameter with the results obtained with the first model.

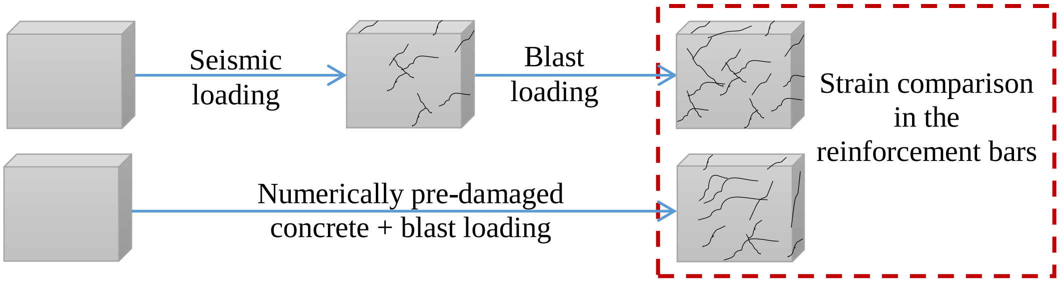

Figure 1. Scheme of the two different approaches used.

1.2. *Hypothesis*

This study is carried out considering the sequence of an earthquake followed by an explosion.We have considered that upper and lower parts of the wall are embedded and each of its sides are simply supported.

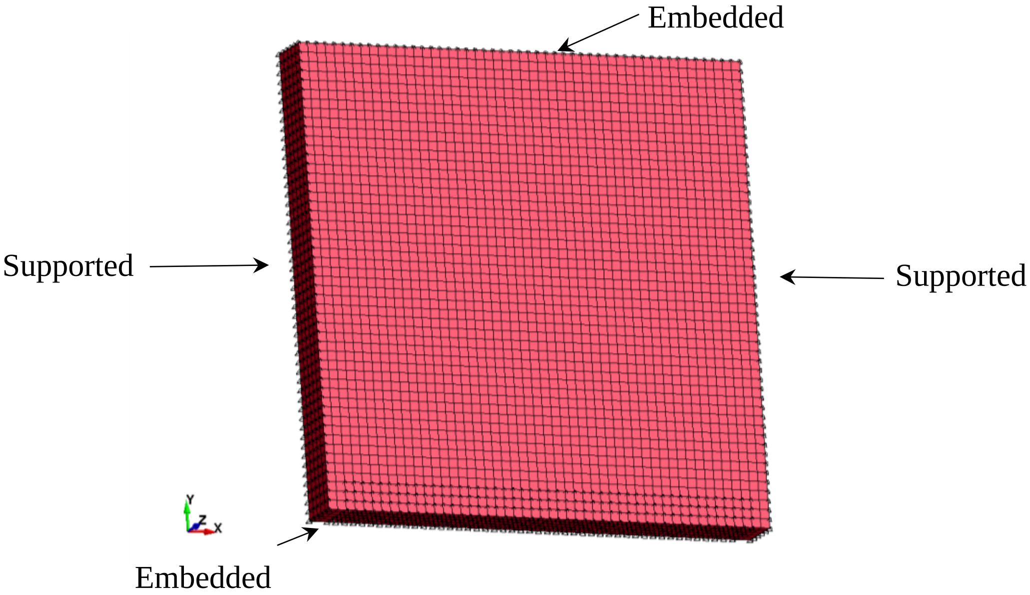

Figure 2. Geometry of the model in LS-DYNA®.

As input data, we have used a response spectrum coming from an earthquake and concerning the explosion load case, we have used a detonation-type case, which corresponds to a triangular pressure curve.

In order to run calculations, we have used LS DYNA® software which allows to perform transient dynamic calculations.

The compressive strength of concrete is 30 MPa, and the yield strength of steel reinforcement is 500 MPa. We model the concrete material with MAT_159 in LS DYNA® software [2; 3] and the reinforcement with an elastic-plastic behaviour, MAT_PLASTIC_KINEMATIC. The so-called model takes into account a pre-damage parameter, traducing a loss of structural strength. It is a way for the user to simulate damages that occurred during the lifetime of a concrete structure such as cracking of the concrete.

This study focuses on the simple structure described in §2.3 and the loads values used are low enough to ensure an elastic behaviour of the reinforcement bars.

2. INPUT DATA

2.1. Earthquake-related data

The first step of this work is to apply onto the RC wall described in §2.3 the seismic loading. We have considered a set of three accelerograms related to the same response spectrum. X and Z axis correspond to horizontal axis, and Y axis corresponds to the vertical one.

Figure 2, 3 and 4 shows the set of accelerograms respectively applied along X, Y and Z axis:

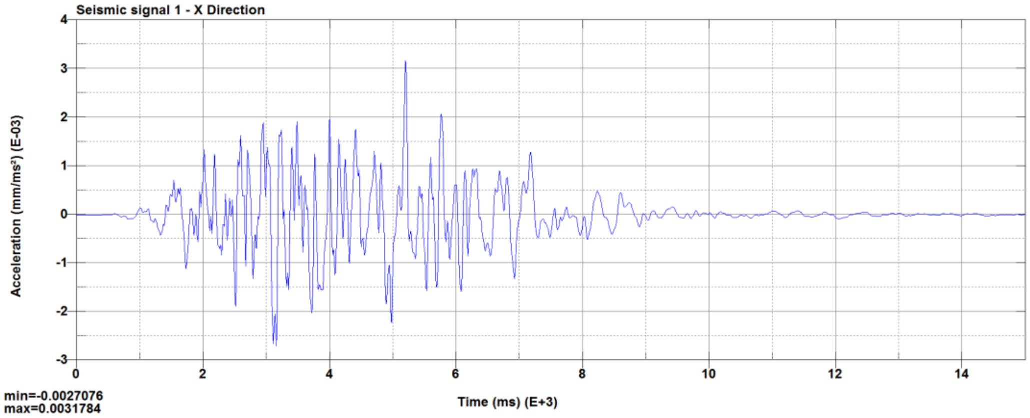

Figure 3. Accelerogram along X axis

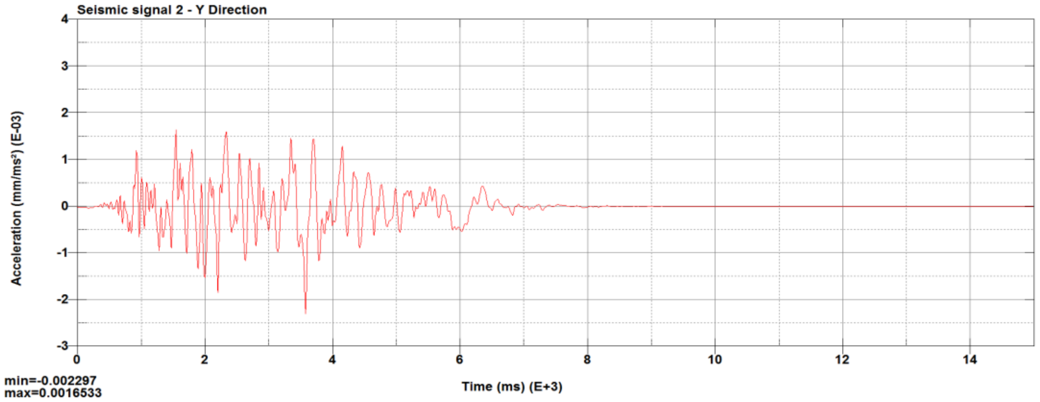

Figure 4. Accelerogram along Y axis

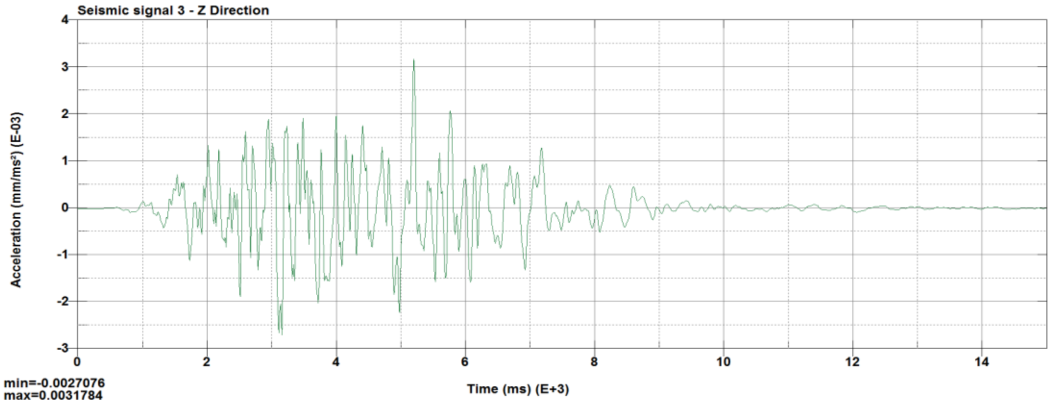

Figure 5. Accelerogram along Z axis

These accelerograms are chosen so that the reinforcement bars remain in the elastic domain. In order to determine the value of the pre-damage parameter for several values of seismic loads, lower levels are tested in §3.4.

2.2. Blast-related data

The overpressure induced by the explosion is considered by applying the triangular load shown in Figure 5 on the whole surface of the wall. The peak overpressure is 1 bar (14.5 psi) for 10 ms duration. It starts at 15.01 s from the beginning of the seismic loading. At that time the seismic loading is ended.

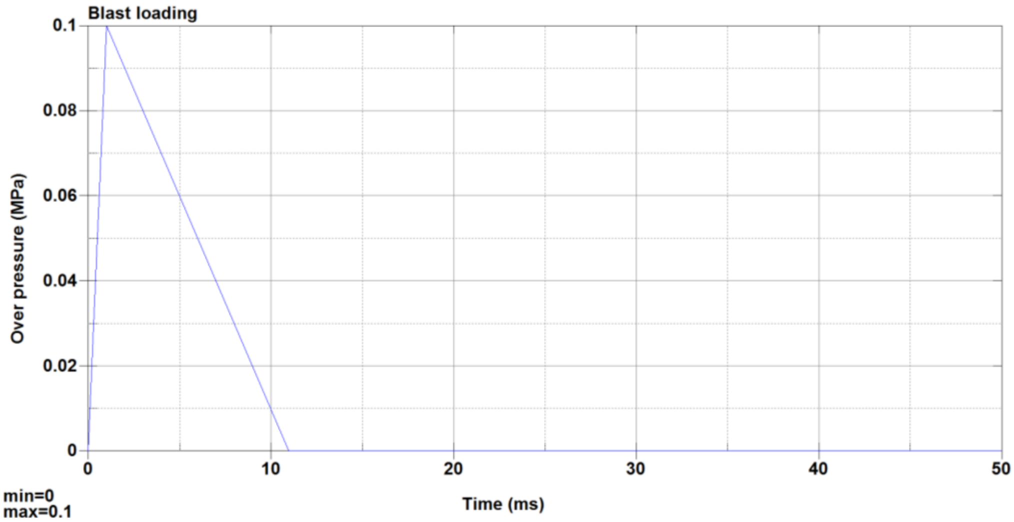

Figure 6. Blast loading applied after earthquake motion (15.01 s).

2.3. Model-related input data on LS DYNA®

The RC wall concrete is 4 m high, 4 m large and 0.4 m thick (157*157*15 inch). The rebar's disposition into the wall is as follows :

- For longitudinal reinforcement bars, on the inner and outer face, we dispose highly adhesive steel bars whose diameter is 20 mm (0.79 inch) spaced every 20 cm (7.87 inch), which corresponds to 15.7 cm²/ml (0.06 inch² per inch) ;
- For transversal reinforcement bars, we dispose 12.5 highly adhesive pins whose diameter is 12 mm (0.47 inch), which corresponds to 14.1 cm²/m² (0.05 inch² per inch).

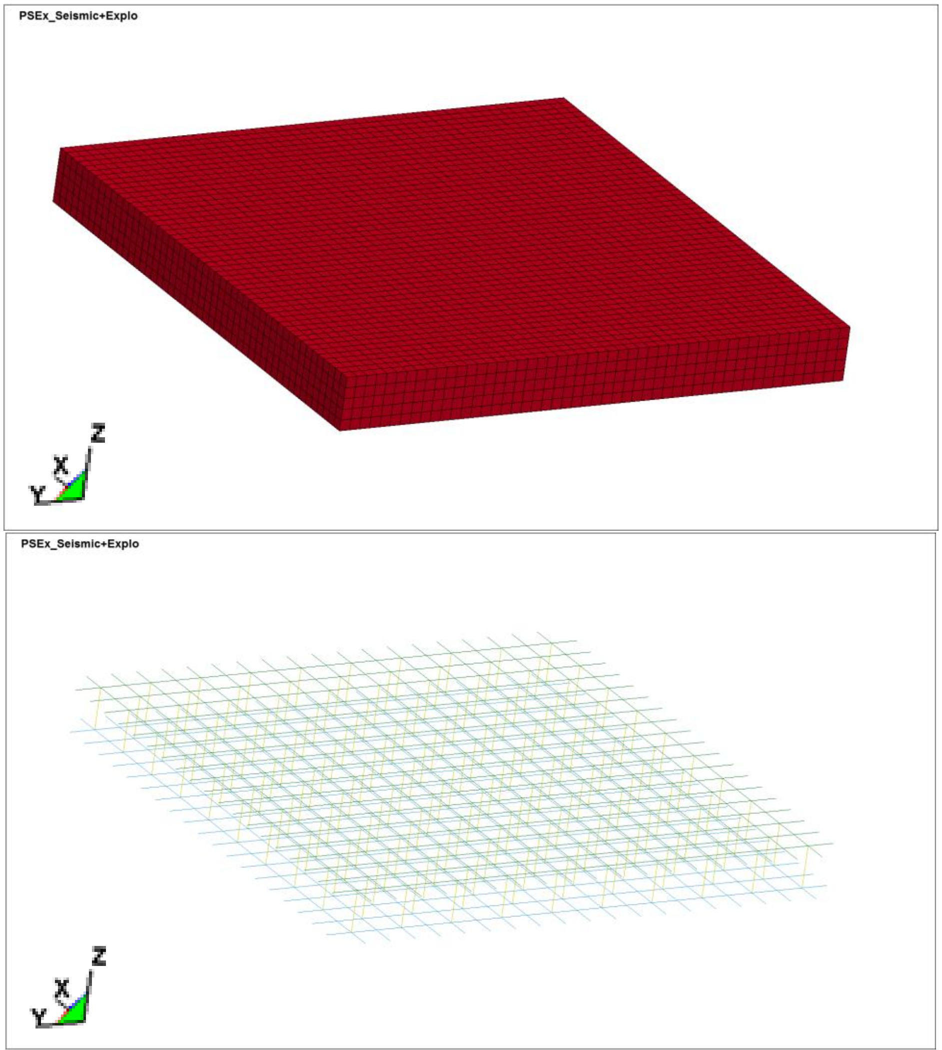

Figure 7. Geometry of the model in LS-DYNA®.

Reinforcement bars have been modeled with 1D bar elements (meshing size is 10 cm, which gives a total of 3,583 bar elements). Concrete has been modeled with 3D brick elements. Meshing size is 8 cm, which gives a total of 12,500 elements for the concrete only. The adherence between reinforcement bars and concrete material is ensured by a Lagrange's contact law, called "Constrain Lagrange in solid" in LS-DYNA.

Concrete material is modeled with MAT_159 [2; 3], which allows the modeling of strain softening in tension and low confining pressure regime. This material compiles different behaviors which are described below :

- *Elastic update*

  Concrete is assumed to be isotropic. The relationship between stresses and strains follows Hook's law.
- *Plastic update*

  After the elastic phase, the concrete adopt yielding or failure behaviors. Yield surface for this model corresponds to the Continuous Surface Cap Modeling (CSCM) [4], which is a smooth and continuous combination of the shear/failure surface and the hardening compaction surface.

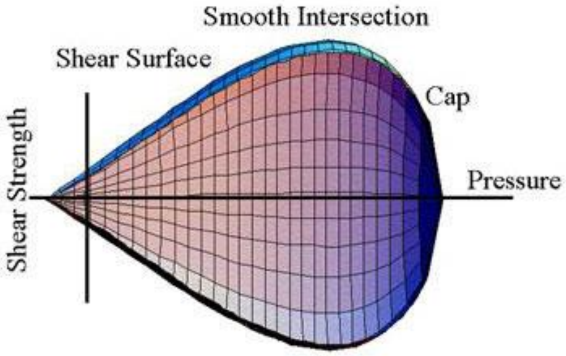

Figure 8. Continuous Surface Cap Modeling model [4].

- *Damage formulation*

  Stresses are defined by the equation :

$$\sigma_{ij}^{d} = (1-d)\sigma_{ij}^{vp} \tag{1}$$

  with :
  - σ_{ij}^{d} the damage stress
  - σ_{ij}^{vp} the stress without damage

The damage formulation contains 2 kinds of damage behavior :

- Brittle damage, which accumulates when tension is applied on the element
- Ductile damage, which accumulates when compression is applied on the element.

The d parameter follows a specific function called the softening function. For further information, refer to the Users Manual for LS-DYNA® Concrete Material Model 159 [2; 3].

The pre-damage parameter d is a way to affect the concrete's Young modulus and also the concrete's compressive and tensile strength. By inputting a positive value of d, the continuous surface cap shrinks, leading to a loss of general structural strength.

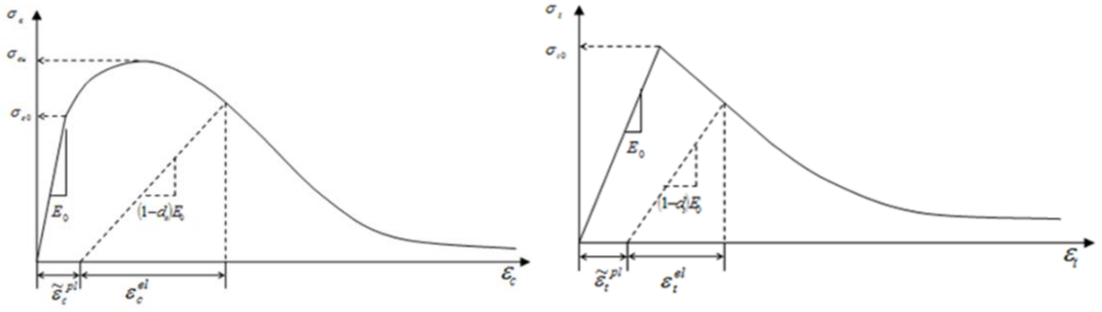

Figure 9. Effects of damage parameter in uniaxial compression and tension [4].

3. ANALYSIS OF THE RESULTS

3.1. Methodology

First, we need to determine the reference of the study, which are results coming from the time analysis of the initial set of accelerograms followed by the explosion load case. We will focus only on the displacement at middle span, the level of stresses into reinforcement bars and the post peak response frequency of the structural element. Those parameters are respectively denoted D_z, σ_s and F_e.

In a second time, we input several value of the pre-damage parameter. By comparing results of the two methods, a link between the design level of earthquake and the pre-damage parameter inputted in the numerical model will be settled. To strengthen the model, a correlation between each parameter is established thanks to a difference ratio :

$$\%_{dif} = \frac{p_x + p_{s+x}}{p_{s+x}} \quad (2)$$

with :

- p_x the value of the parameter found with the pre-damage model ;
- p_{s+x} the value of the parameter found with time-based analysis with an explicit time step.

3.2. Results of the study

3.2.1. Time-analysis post-processing

Several tests lead to conclude that the threshold of plasticity is reached for a level of design earthquake amplified by 50%.

Hereunder, the results of the post-processing with the model considering time calculation of the seismic load and then blast loading :

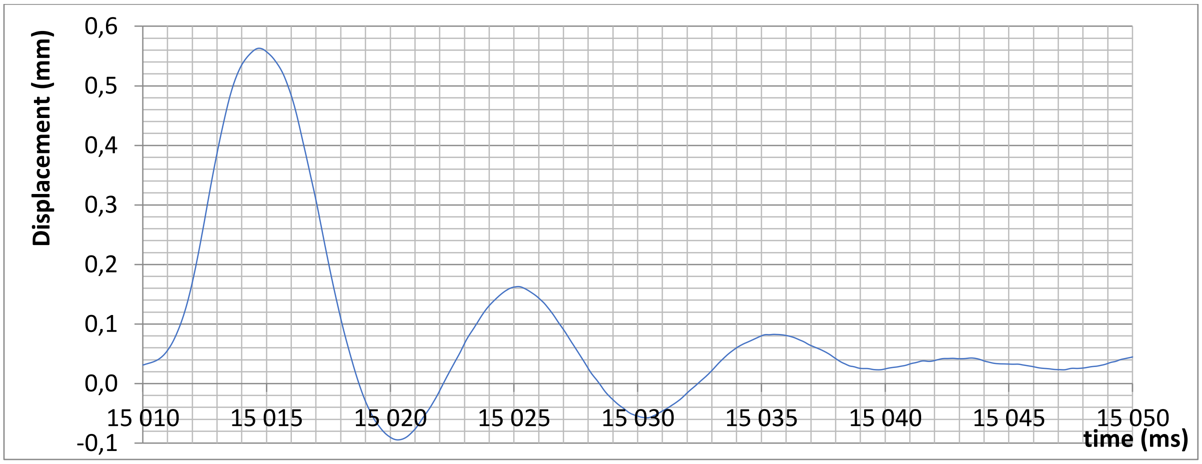

Figure 10. Displacement at middle span in the Z direction after blast loading.

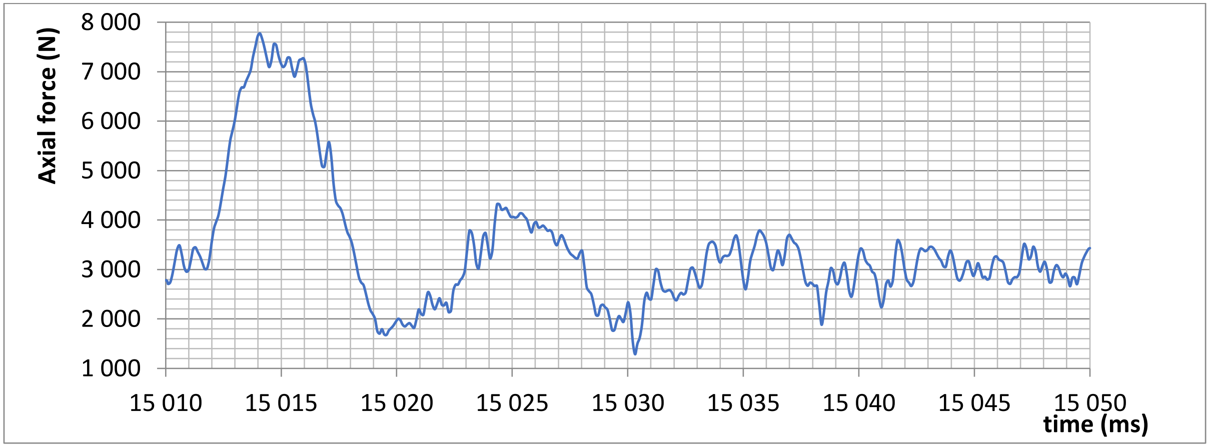

Figure 11. Axial force in reinforcement bars at middle span after blast loading.

In figure 10, by doing the difference between the peak displacement at 15,015 ms and the initial value at 15,010 ms, we obtain a displacement of 0.53 mm (0.021 inch) at middle span. We can also determine the post peak response frequency of the wall which corresponds to 100Hz.

Figure 11 gives the axial force in a bar element at middle span also. Using the same method than displacements, we obtain an axial force of 3.89 kN which corresponds to 12.4 MPa (1,798 psi) of stresses within reinforcement bars by multiplying this value by the section of 20 mm (0.79 inch).

3.2.2. Pre-damage post-processing

Ten levels of calculation have been run for a pre-damage parameter d varying from 0 to 0.9 .The evolution curves of those parameters according to the value of the pre-damage parameter are plotted below :

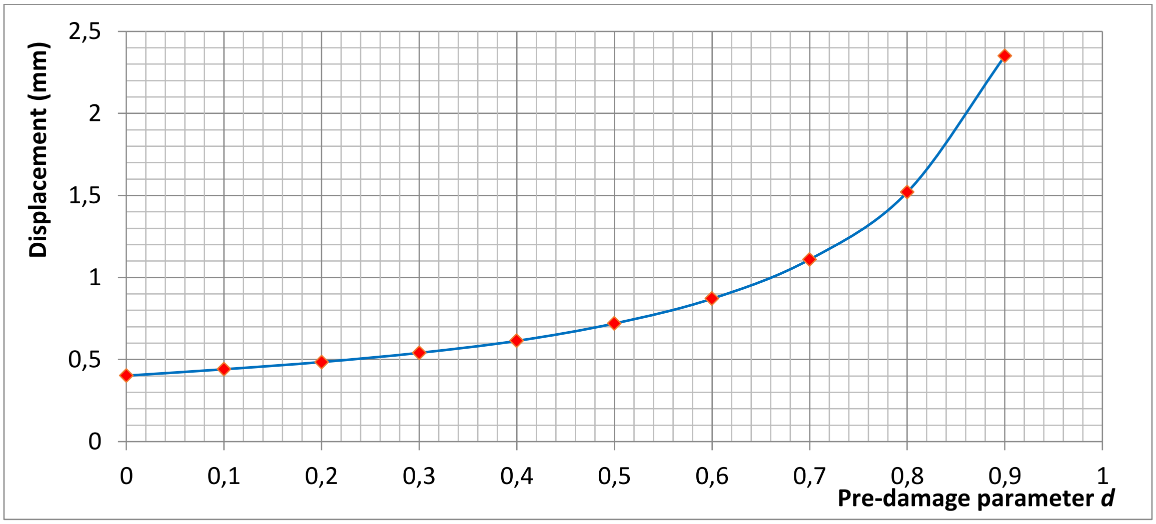

Figure 12. Displacement at middle span versus pre-damage parameter.

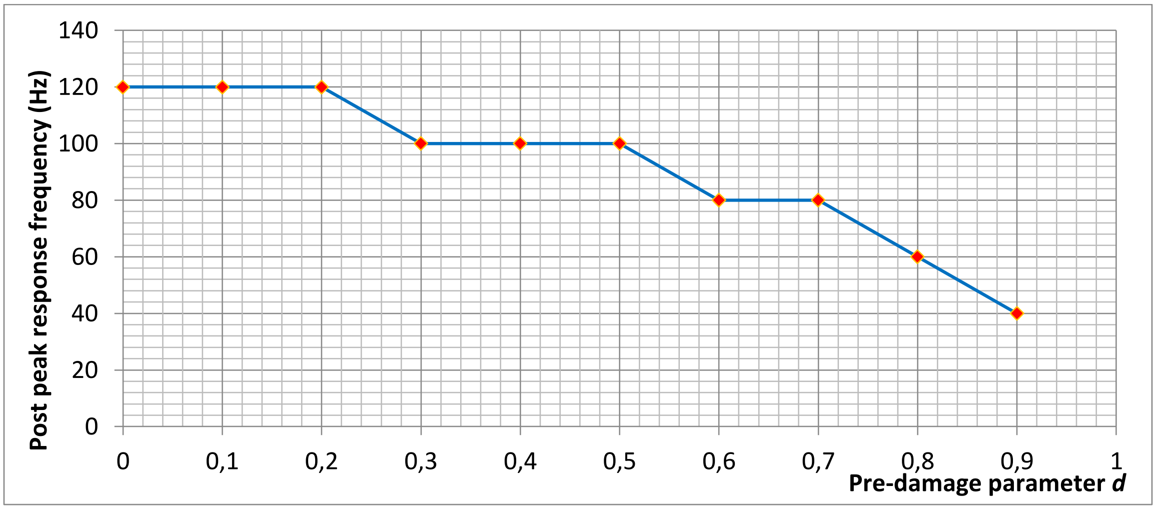

Figure 13. Eigen frequency versus pre-damage parameter.

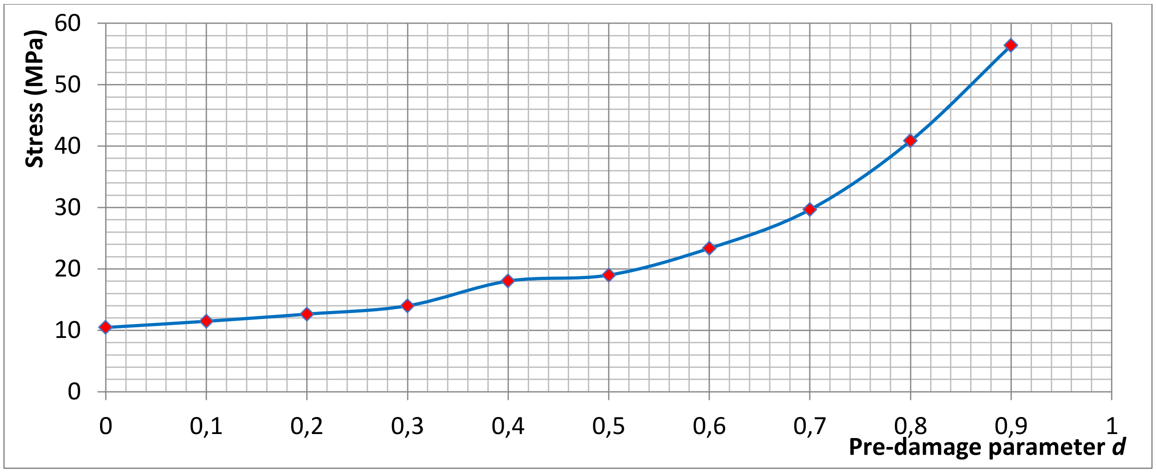

Figure 14. Stresses within the reinforcement bars at middle span versus pre-damage parameter.

3.3. Analysis of the results

Regarding the displacement at middle-span, Figure 12 shows that for a pre-damage parameter equal to 0.3, we have a difference ratio of + 2% in comparison with the value obtained with the time analysis calculation. For a pre-damage parameter equal to 0.2 the ratio is close to -9%.

For the pre-damage parameter equal to 0.3, we find, from the displacement curve, the post peak response frequency equal to 100 Hz. This value corresponds to the one find with the time-based analysis with the design earthquake. Until this step, the correlation is assessed as correct.

Figure 13 shows that the stress obtained at middle span in the reinforcement bars are closed to the value obtained with the time analysis (12.4 Mpa / 1798 psi) for pre-damage parameters between 0.2 and 0.3 with difference ratio of -19 % and 11% respectively.

Thus, we can conclude that the final value of the pre-damage parameter corresponding to the design earthquake in order to keep the elastic behavior of the structure can be decreased to d = 0.3. This value is, as forecasted, lower than the decreasing factor 0.5 recommendation applied on every parameters which relate to the level of cracking. It highlights the fact that this decreasing value sets a margin that can be reduced in the case of a numerical model of transient dynamic load case.

3.4. Correlation for different levels of design earthquake

The second approach of this study is to correlate others levels of earthquake with pre-damage parameter value. We run calculations with a decreasing factor of the seismic design level defined in §2.1 and noted by SDL. We consider 4 seismic levels which correspond to 20%, 40%, 60% and 80% of SDL. Same parameters are assessed in order to set the correlation. Hereunder, a sum up of the results :

Table 1. Results for the different levels of design earthquake.

Seismic level	D_z (mm)	Difference ratio		σ_z (kPa)	Difference ratio		Final pre-damage parameter associated
		%dif	Pre-damage		%dif	Pre-damage	
80%*SDL	0,529	-8,30%	d = 0,2	1,684	-4,30%	d = 0,2	0,3
		2,30%	d = 0,3		5,90%	d = 0,3	
60%*SDL	0,509	-4,70%	d = 0,2	1,620	-7,50%	d = 0,1	0,2
		6,30%	d = 0,3		1,80%	d = 0,2	
40%*SDL	0,479	-7,90%	d = 0,1	1,525	2,90%	d = 0,1	0,1
		-1%	d = 0,2		13%	d = 0,2	
20%*SDL	0,457	-4%	d = 0,1	1,455	-4%	d = 0,1	0,1
		6,10%	d = 0,2		-5,90%	d = 0,2	

The pre-damage parameter evolves in coherence with the magnitude of the earthquake and low difference ratios are found for the same pre-damage value.

4. CONCLUSION

This study has been carried out in a first approach to produce a design and assessment tool more effective than usual one. In fact, previous methods in order to take into account cracking rate of a structural element traduced margins which were too much penalizing for our case and may have resulted in an over-design of the structure. With this study, we prove that those margins can be reduced, thus it induces cost-effective design methods.

This work is the first step to establish a reliable tool for the use of a numerical finite element model in order to correlate a level of resulting losses of structural strength after an accidental load case and the pre-damage parameter input in the software. In further developments, the study could lead to the assessment of the parameter in case of more complex structures such as global building with links and singularities. Moreover, this study is limited to the elastic behaviour of the reinforcement bars ; thus a nonlinear approach of the pre-damage parameter could be later assessed, especially for nuclear safety re-examination works.

Additional works will be done in order to extend the domain validity to the plastic domain of the reinforcement bars and also to different loading cases such as impacts or drop loads.

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