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A Simple Vulnerability Model to Assess the Seismic Risk

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Abstract: **Knowing the behavior of building structures through the interpretation of the results of different tests is indisputably the most correct approach to mathematics, mechanics and engineering. Among other things, should be given proper attention differentiation of the analysis, that our approach to each of them will manage to get the necessary and appropriate results in relation to the time spent for each of them. In the material that follows, I'm focused to address the concept of Vulnerability, for defining it as a practical factor in assessing the structure risk, mainly from seismic actions. Serving this concept I have exploited nonlinear analysis (PUSHOVER) and within the segment in which appeared that the structure possess resistance, I have realized two models of vulnerability. Mechanic model that provides physical state of the structure for different levels of seismic force and Economic model which develops the mechanical model by using economic parameters in terms of reinforcement. The concept of mechanical model aims to liberate the local performance of the structure by modeling its global performance. The concept of these models is addressed in the following paragraphs, together with reflections and improvements about this models. This vulnerability model has an advantage as it is very simple to be realized furthermore is more applicable for the purpose of strengthening the existing structures, as conducts an accurate correlation between the performance of the structure, risk, the level of restoration and total cost.**

Keywords: **Vulnerability model, Risk, LD (lower deformation), HD (higher deformation), CP (curve of plasticization), Mechanic Vulnerability, Economic Vulnerablity**

1. INTRODUCTION

Seismic events have significant consequences for the construction works. Nowadays have been developed and perfected numerous techniques to calculate seismic operations, generally incorporated with the application of technology, from which we get a wide spectrum of results. If for a moment assume that regarding to a specific structure taken under consideration, we are interested to know the internal forces. As far as we are modelling correctly physical and mathematical models, either with static equilibrium methods, or energetic methods, we will ensure the results we were seeking for. Assuming that we provide sufficient accuracy, our expectation is that these results will be the same. At the same topic we can ask: which method would be the right one? The force method, deformation method, finite element method, etc. What analysis to perform?: Linear analysis, nonlinear analysis, etc. In contrast to the actions of external forces, Cession, temperatures etc, earth shaking action is reflected with a complex situation in structure, where performance is not only a function of the intensity of external action but also of the selected structural analysis and the structure itself.

'Risk' and 'Hazard' are both contemporary concepts completing each other (in some cases used also instead of each other) when the topic is about the treatment and management of seismic events. If would use simple words,we could say that seismic 'hazard' is a function: H = f (PGA, probability, site, structure, time, etc.), In the same way we would say for 'risk' expressed as: R = g (PGA, probability, site, structure, timing, etc.). Determining the risk, a very significant expression would be:

Risk = *Hazard* x *Vulnerability* x *Exposure*: ……… (1.0)

If we have an objective evaluation of each of the above parameters, assume from "zero" to "one", for example: H = 0.7, V = 0.8, E = 1, will get: R = H · V · E = 0.7 ·0.8 · 1 = 0,56. Such a situation will be described as: The risk that threatens a given structure exposed 100% to various risks that have a chance to occur with probability 70% and structures have a 80% vulnerability, is 56%. The following graph is very significant for risk and exposure, which are two factors based on our knowledge, observation and our ability to predict [1]. But the most important factor in the relationship remains, I think, vulnerability, because it is simultaneously the knowledge and how we should conceive an existing structure. The vulnerability is not dependent on time, but it is our observation versus engineering structures.

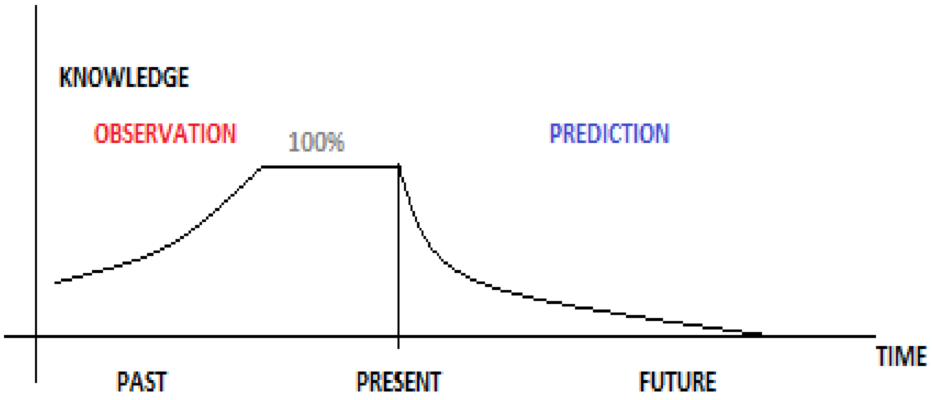

Figure 1. Time-Knowledge relationship[1]

An approach towards the concept of vulnerability is by categorizing different structures with specific similarities in classes that have a high possibility to have the same performance or behaviour to certain risks [2] .A approach to risk assessment and vulnerability is through the statistical data registered in countries which have experienced a catastrophic event [3]. When we talk about risk, Hazard and vulnerability refers to the possibility or not that a structure will achieve a specific damage.

PD = f {(R)(H)(V)}[5] ……..(1.1)

PD is the *probability* that damage will result from a specific event;

R is the probability that the hazard will become an event;

H is the hazard;

V is the vulnerability;

The relationship above connects the possibility of damage to the risk, hazard and vulnerability, but reverse some variables may derive from this relationship, as can be:

V=g{(PD)(R)(H), ….. (1.2)

Their results are not part of this paper as far as these principles are developed in advanced techniques of risk assessment and vulnerability under HAZUS, as the most important issue is the compatibility of the respective models correlation (different factors with different units correlated to produce another factor). I would like at this stage to mention another approach concept of vulnerability.

$$V = \frac{\textit{Total value of damage}(R,H,E)}{\textit{Total value of building}} \quad [6] \qquad \text{……} \ (1.3)$$

The introduction of economic concepts in the light of the vulnerability of a structure has great importance and especially since the concept of vulnerability itself has become part of engineering assessments in such cases where certain events have brought disastrous consequences in the economy. Economic approach, although can be expressed compared with other factors with a certain value which is much more clear to be understand, holds so many other factors related to social-economic factors without correlation with engineering approach to the treatment of risk problems. From the above might be said that the vulnerability is a factor that indicates the possibility that an existing structure, for a seismic event exceed in such a performance condition, whose parameters are within a certain range that defines in itself a certain class of vulnerability.

2. DISCUSSIONS ABOUT THE TOPIC

In parallel we are considering an illustrative example, which in reality has a very low[1] probability to happen but has a valuable meaning. The case consists of two different structures but that exhibit the same performance versus values.

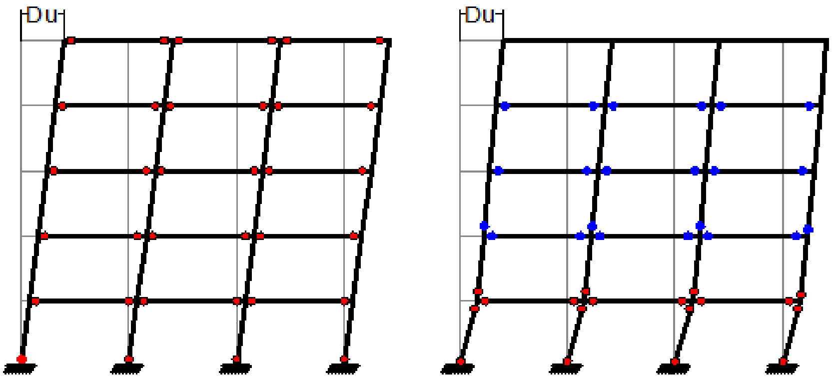

Figure 2. Plastic mechanism of the structures: Model A (left), ideal designed structure; Model B (right), soft storey structure

By observing figure 2, plastic mechanisms and the capacity curve figure 3, shows that the structures have the same performance for a given level of seismic activity. This results are the same in terms of spectral displacement or acceleration, displacement at the top of the structure and shear force in the base. To be more accurate for the above results should be recalled that the level of equality is within tolerances in engineering and not in mathematics.

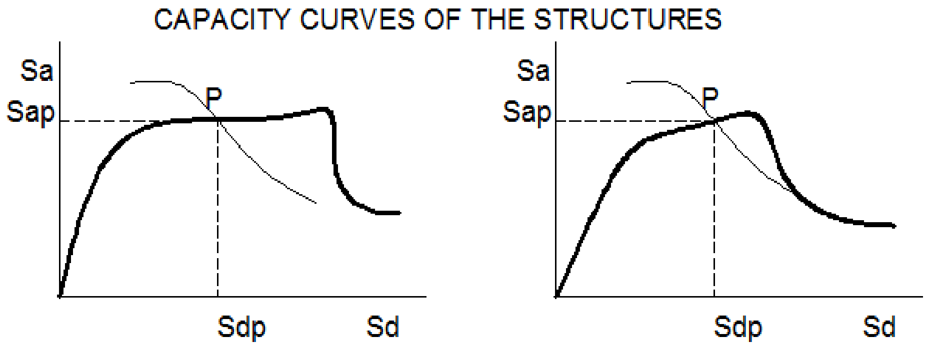

Figure: 3. Capacity curve of Model A(left), Capacity curve of Model B(right)

Despite interpretation of the results, clearly we can not talk here about the same typology and structure behaviour, or otherwise can not expect the structures to be within the same level of vulnerability. Let's take another hypothetical assumption: there will be a seismic event, identical to that assumed in the analysis for the above structures, as well the behavior of the structure will be identical with the above results. This kind of assumption is the case: when within a certain area has been a seismic event and are in the process of assessing the damages, or when we are in the evaluation of existing structures and want to know the degree of vulnerability or their vulnerability to the expected event.

For restoration or strengthening the MODEL A, must take into account the increased capacity of 30 beam sections and 3 column sections which have reached capacity limits. For MODEL B, we have 12 columns sections and 6 beams sections which have reached capacity limits and 18 beam sections and 4 columns sections which have achieved a high level of deformations but they are far beyond capacity. For the first case, we would have 15 = (30 + 3) - (12 + 6) sections more which would require intervention in increasing capacity. The same problem can be raised for the reinforcement phase before a seismic event. To maintain the regularity of the structure "A" should be made interventions in each element of the structure to enhance the capacity in a proportional way, or if this is not respected, we will destroy the regularity of the structure. In case B the intervention should be done only in special elements that would pass the first the capacity limits. By following this strategy is achieved an improvement of structural regularity. Translated into costs for a reinforcement procedure, would say that the amount of capital spended is proportional to the number of elements which will be reinforced.

[1] It refers the Model A that is very difficult to find a structure constructed with absolute regularity

In these moments lets make an assumption: exists 10 classes of vulnerability (V = 0 not vulnerable, more vulnerable V=9) for fame structures (included the structures of Model A and B).

Vulnerabiliteti	Model A	Model B
Ekonomy	7	4
Structure	1	8

Figure 4. Table for the vulerability approach of the models

At first sight it seems to have a certain contradiction between the results above, the building with a little vulnerable structure has a high vulnerability to economic and what is more vulnerable structure have a smaller economic vulnerability. In our disfavor is the fact that we do not have a universal evaluation of the vulnerability, but it is in our favor this results.

How should we understand this?

Refering the seismic level taken into consideration, supposing that would be an exceed at a certain amount, as the model B will develop a soft storey mechanism and its eventual destruction couldn't be avoid. A destroyed structure has theoretically a vulnerability of 100% ,or the concept of restoration would consist of building from scratch the entire structure. Model A, based on the graphs of capacity curves will continue its post-elastic phase while for the same seismic level, model B will form a soft sorey destruction mechanism which will be called the collapse of the entire structure despite that most of the structure has a strain condition lower than model A. In a hypothetical assumption as B structure was reinforced in the soft storey mechanism (consisting of a very limited restoration area but however the most important area of the structure) by adjusting its hardness, situation would be completely different. The risk is higher in this case for model A, wich would reach the limits of its plastic properties. The concept of reinforcing and reinforcing strategy plays a relative role in the values of vulnerability.

Let us mention vulnerability assessment methods through evaluation of fragility curves for structures (probability distribution models) [8]. Fragility curves requires fragility building models, presented in the following figures.

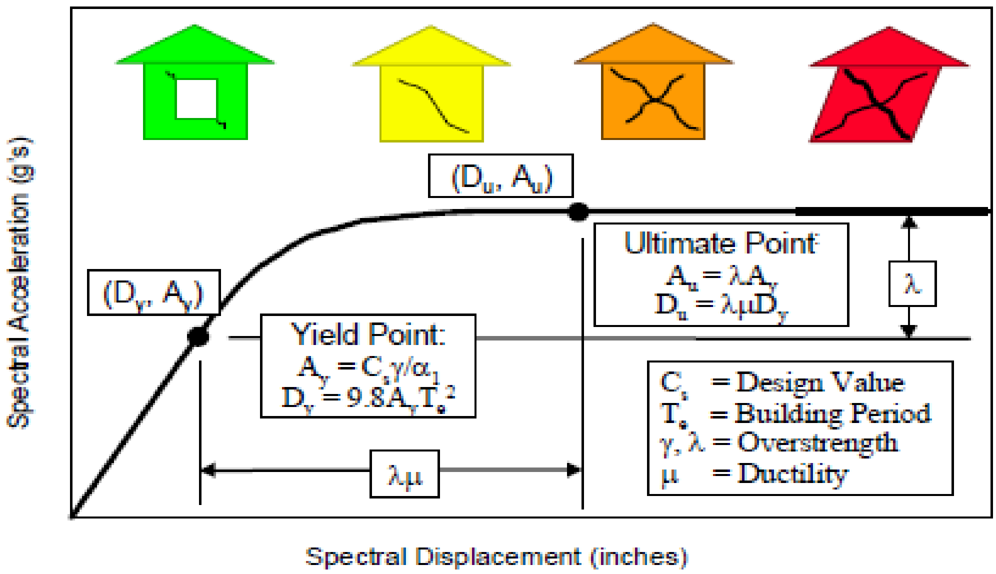

Figure 5. Fraility model

The main steps would be: 1- analysis of the structure and development of fragilty model curve through capacity curve of the building. 2- classification of the structure and selectioning of longnormale distributions coefficients [8].

$$P[ds|\ S_d] = \phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right] \quad \text{.... (1.4)}$$

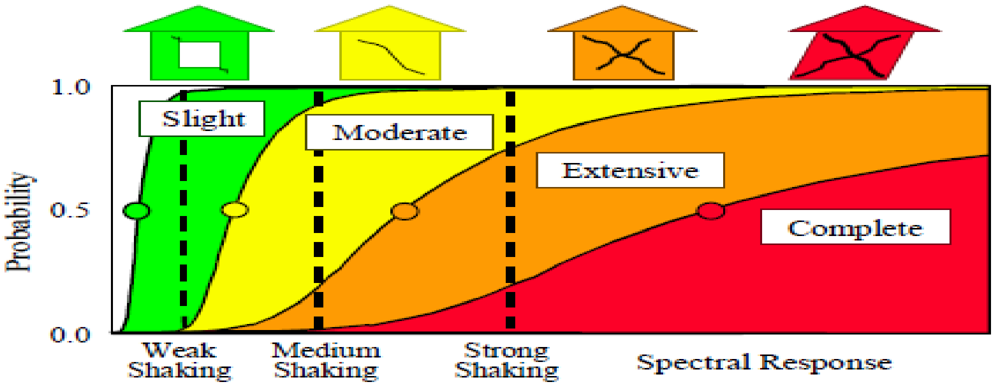

Figure 6. Fragility curves from the equation (1.5)

Starting from the figure above in a simple way they express that for a certain level of seismicity we will be able to define the probability for wich a structure will exceed a proper level of deformations. Widely accepted are 6 damage levels as follow: Level 0-No Damage; Level 1 Slight Damage; Level 2-Moderate Damage; Level 3 Substantial Damage to heavy; Level 4-Very Heavy Damage; Level 6-Destruction. The above levels recorded in the capacity curve modified for the purpose of building fraglity curve, refers two main conditions, the initiation phase of yielding (plasticity) Δy and Δu limit phase. Methodologies developed in principle are the same but they differ in the values of coefficients as well as the respective limits of deformation conditions [7] [8] [9].

By turning back to the previous example, where in review are two models A and B, for the fragility analysis the first difference arises in the tansformaion of the capacity curve in a fraglity model. By exploiting the respective coefficients can build on the same shape of figure 6 fragility curves for deformation and seismic hazard levels. Interpretation of the results would be in this form: for the level of seismic hazard "a", the probability to have minor damages P_S=20%, moderate P_M=35%, and higher P_H=45%. For a level "b" these values are different. At this moment we have to do some reflections:

1. We know that probability is not translate into events. The probability to have a certain deformation doesn't mean that eventually will happen that damage for the seismic level.
2. Secondly a certain level of damages (deformations) assigned to the capacity curve of the structure would translate to the same level of deformtions in the structure elements, that is not true.
3. Given the percentage level for major deformations in the structure does not brings extra information on the elements which have achieved considerable damage and where are positioned, whether or not there could be a possible storey mechanism.

From this reflections may raise the question: How can we develop an analytical approach which independently from experience around to give us objective judgments on:

- Performance of the structure in global and local terms.
- Seismic Risk as a function of the structure and seismic hazard.
- Vulnerability of the structure as a function of the structure and seismic hazard.
- Vulnerability of the structure as a function for the reinforcement purpose.

3. A MECHANIC VULNERABILITY MODEL

Given the existing concepts related to structure, a similar approach but with recognition function of each element behaviour I am proposing to build models according to which is defined the class of a structure in accordance with the behavior of each element and the structure itself. Similarly with fragility curves, fragility model must be replaced with elasto-plastic behavior models, for each specific element of the structure. This model not only should be mathematical, but must have appropriate correlations with its reinforcing strategies. The next step should be modelling the graphs not by probabilities functions but through statistical data of the structure itself, which constitute the essence of the probability concept.

MODEL C

Model C consists of a reinforced concrete structure, 4 storey plain frame designed in acordance with EN-1998 recommendations. On this strucure is performed a nonlinear static analysis, gradual loading, "PUSHOVER" executed in SAP2000 program.

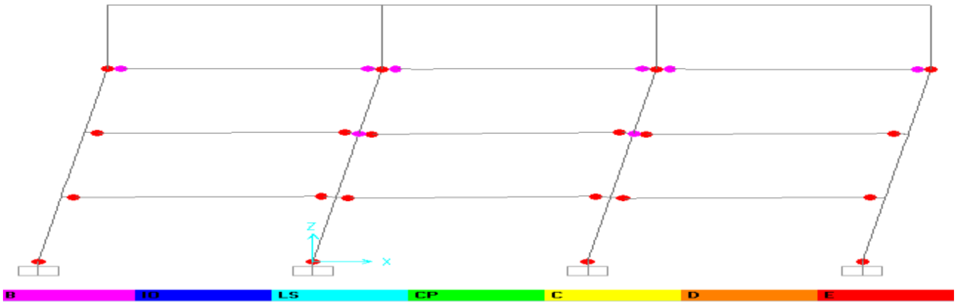

Figure: 7. Plastic hinges mechanism of the C model

Figure 6 shows schematically a Pushover analysis phase, in which very clearly is expressed the most possible mechanism of destruction for the structure. For a loading phase we are able to judge the number of elements that belongs to a state of deformation. Figure 8 is a graphical representation of what we said above, where the axis of abscissa is the spectral shift for the respective loading phase, and the ordinate is the ratio of the elements which display a deformation state.

To make a comparison with the fragility curves in this case, we would judge or a certain level of deformation Sd' :

- For fragility curves:

$Sd_{element}$ = k Sd' (k- takes into account the form of the first deformation mode to make the connection between local and global deformation)

P(Sd=Sd') = P_0 (expressing possibility of the structures found in a certain deformed condition)

- For figure 7:

$Sd_{element} = Sd_{Capacity}$ (according to the specifications of the capacity curves for each respective element)

Sd=Sd' → $N_1=No_{elements}$ $(Sd_{element}=Sd_{elastik})$; $N_2=No_{elements}$ $(Sd_{element}=Sd_{yield})$; $N_3=No_{elements}$ $(Sd_{element}=Sd_{colape})$

According to the results shown in the graph of figure 7 we are able to know the number of elements in a certain condition, not in probability language but of numbers which give us the deformed state and the level of plastic hinges or potential destruction joints.

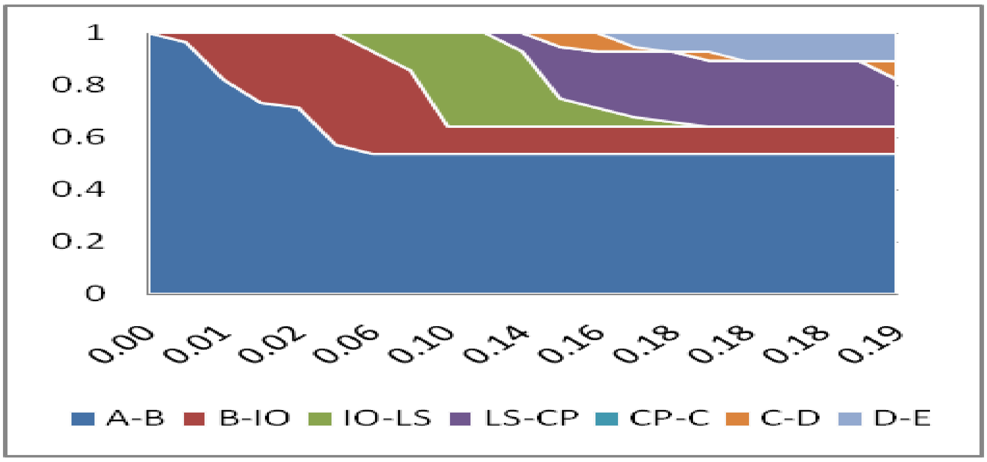

Figure: 8. Mechanic Vulnerability

At first sight it seems like that such a graph reserves a very small surface for the elements which have undergone large deformation condition, or otherwise in potentially desctruction, which is translatet into a perception: the probability to have a state of high deformations is very low for a certain level Sd'. Recognizing that we have made a correct modeling and Pushover analysis is correct (this is out of our topic), what should we say is that: the probability that x% of the elements are in a state of "IO[2]" deformation, if the entire structure has a Sd' performance, is equal to" 1 ":

$$P_{X\%\rightarrow IO/Sd'} = 1 \qquad \text{.... (1.5)}$$

Taking into account the errors in modeling and Pushover analysis inaccuracy, eleminate paradox of probability "one" P = 1, and being mathematically correct the expresion is formulated: the probability that x% of the elements are in a state of "IO" deformation state, if the entire structure has a performance Sd', is very high, or we are theoretically dealing with a fact. And this event, almost the deformations are a fact perhaps in a limited number of elements with large deformations that could cause to be a plastic mechanism that has a certain chance of crumbling.

4. AN ECONOMICAL VULNERABILITY MODEL

The above data have a practical value in the issue of strengthening the structures, as can be identified for certain condition deformations (or seismic action) the quantity and quality of reinforcing interventions. Each deformation level in the capacity curve of an element represent directly a certain level of reinforcement. Based on this principle we can build a vulnerability model based on the amount of destroyed elements. This vulnerability model has some specifications that are presented below.

- Separation of structure in elements which have similarities in: 1 material; 2 types of element (column, beam, etc.); 3 curve of capacity,
- Define the deformed conditions specified in the capacity curve for each typology of plastic hinges referring to the need for reinforcement: 1- for stress conditions from 0-F y → no need for reinforcement; 2- for stress condition from Fy-Fu →reinforcement is needful to increases the resistance; 3- for stress conditions > Fu → reinforcement is needful to increases both resistance and strength.

Referring the graph of figure 7 and conditions for forming the model we take:

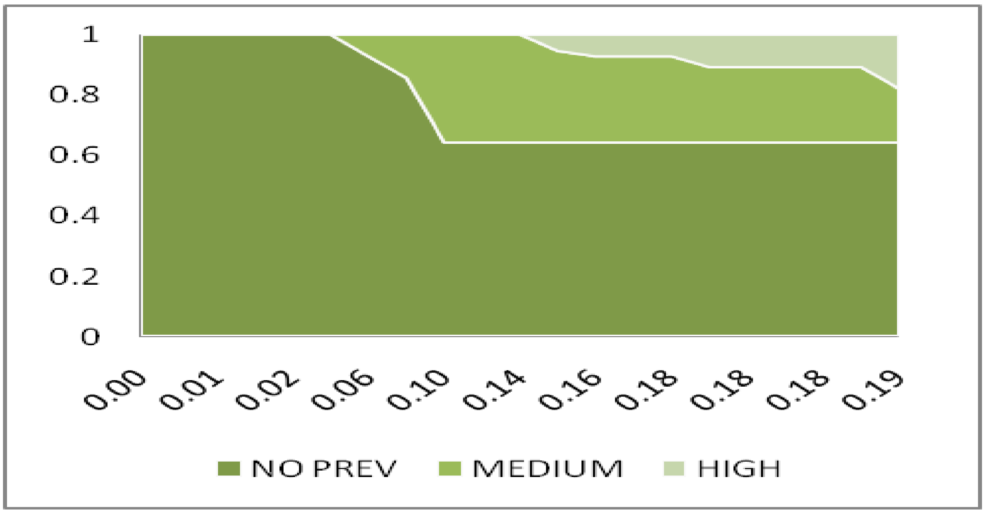

Figure 9. Mechanic Vulnerability in terms of interventions in the structure for a level of performance

The graph gives the percentages that for seismic hazard level we do not have interventions (NO PREV), to have average interventions (MEDIUM) or have substantial interventions (HIGH). Production of each level for reinforcement with the market value for the realization of such an intervention provides monetary value spent to achieve the appropriate interventions and their sum gives the value of all interventions at the level of performance. The ratio of the amount needed to make an intervention reinforcement with a total value gives the vulnerability of the structure. As the total amount may refer to the total value of the structure but there are cases when the value of the structure is not a function of the structure but also the social and cultural values, a total value admissible is that: supposing that the whole structure will be enforced assuming that each element is "destroyed", has neither resistance and stiffness. This value would deal if we had a case where the graph of figure. 8 have a value: HIGH =1 and it would multiply than the market value.

[2] IO- imedate occupacy

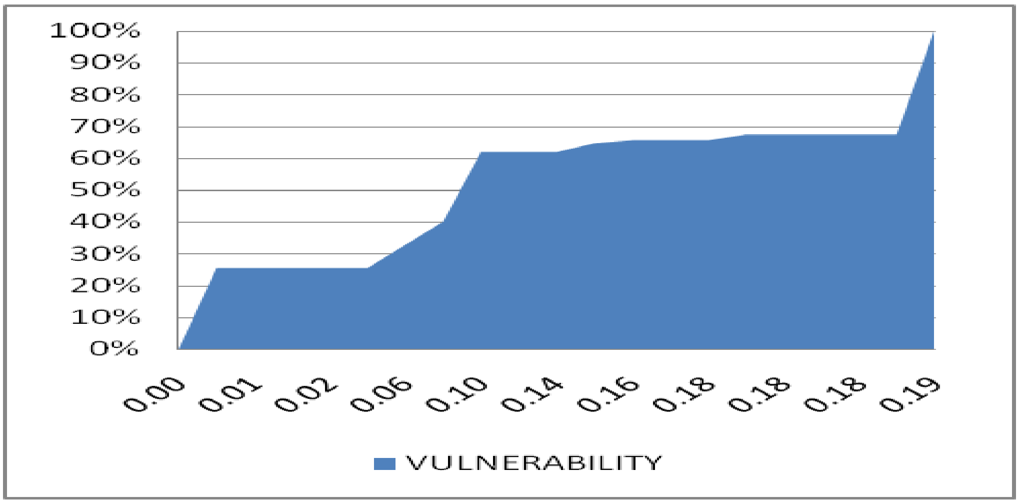

Figure: 10. Economical Vulnerability

The above graph expresses the economic vulnerability for a structure as ratio of the value spent on restoration interventions in constructive elements towards a restoration value for e destroyed structure.

5. INTERPRETATION OF RESULTS

The shape of the graph is displayed with two parts almost horizontal and three steep parts. The first branch of the curve connect "zero" with the start of deformations. The first horizontal branch (area of Lower Deformations, LD) showing the minor damages to the structure and refers light earthquakes compared with designed earthquake. The second horizontal branch (area of High Deformations, HD) corresponds to a state where the structure has formed the destruction mechanism and the structure is in the area of global yielding. Branch connecting two horizontal levels (Curve of Plasticity CP), is the area of the beginning of plastic hinges. The third branch shows the capacity of the structure, where for a further incrisement we have to do with the eventual destruction of the structure.

6. REFLECTIONS AND IMPROVEMENTS

The above graphs are constructed on the basis of data obtained from the results of tests performed by SAP2000 for model C. In the abscissa axis are spectral displacement achieved values, but in analogy with them can be found even spectral accelerations or maximum accelerations site (PGA, peak ground acceleration) that correspond to the deformations level.

Further improvements to the methodology associated with the modeling phase of structural and non-structural elements and presentation of the outcome of these elements in relation to their strengthening.

Numerous studies for different structural models will register the different forms of vulnerability graph to determine the different vulnerability classes in terms of:

- Lower level of deformations, LD
- Higher level of deformations, HD
- Curve of plasticity, CP

7. CONCLUSIONS

Addressing the above topic was given matter the strengthening of structures and developing simple models of Vulnerability which independently for a given structure can give us:

- Structural Vulnerability Assessment as a state of completeness of elements, not only the global behavior of the structure.
- Evaluation of economic vulnerability expense ratio reinforcement with maximum expenditure necessary.
- Correlates of structural and economic vulnerability.

Models presented above for the vulnerability are easy in formulation, assessment and practical interpretation and very effective in time to create the right impression engineering for existing structures.

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