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A multilevel decision-making approach for the resilience assessment of industrial plants in seismic prone areas

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Summary

In the present work the problem of the seismic resilience of industrial plants, characterized by a sensitive interconnection among single facilities, has been investigated.

A brief introduction about the typical problem the industrial facilities are affected after a seismic event was provided. By this means it was possible to clarify the dimension of the problem and the extension, spatial and temporal, of the economic exposure industrial plants are affected. Then, the focus of the current method of analysis of industrial plants has been proposed, showing the differences among the vulnerability, risk and resilience. It was observed that: vulnerability methods are not suitable to provide information of the economic exposure; risk analysis can provide an insight about the economic exposure immediately after the seismic event, but does not provide any information about its temporal evolution; resilience analysis can fill the lack of information provided by the risk analysis, giving an overview of the temporal evolution of the economic exposure.
Notwithstanding the importance of the resilience analysis, a lack in the current scientific literature was observed, evidencing that only risk analysis is usually adopted, providing several methodologies, qualitative and quantitative as well.

Then, the aspect of the resilience analysis was deepened, specializing the general concepts for industrial plants. In particular the problem was faced from two sides. At first the behaviour of stand-alone facilities and the methods for the resilience assessment was analysed. Specific methods for the estimation of the consequences associated with the resilience analysis, i.e. the residual functionality $q(t)$, the recovery time t_{rec} and the recovery path, were defined. Therefore, the interest moved to inter-connected facilities, for which

the concepts of the reliability of systems are enriched with further aspects to make them applicable for the resilience assessment.
With such investigations, a detailed method, based on the PBEE framework, for the resilience assessment of industrial plants and facilities prioritization was proposed, filling the gap of current literature.

Notwithstanding the evident complexity to perform detailed analyses on a huge set of facilities, variously connected among themselves, could be too cumbersome, a multilevel procedure is proposed. The aim of such a procedure is to provide a global, but rough, overview of the results at the first level, performing simplified analyses (for the definition of the structural performances and the estimation of consequences), and specializing the results at the next levels by means of detailed analyses targeted on few critical structures. The multilevel procedure is intended to be a tool that simplify the detection of critical elements within the whole Plant, performing on them detailed assessment.
The procedure is based on three levels:

- the *first level* is based on the execution of simplified analyses at the plant level; for the estimation of consequences a specific method, based on a tabular format is developed;
- the *second level* focuses on refining the structural performance and the estimation of consequences of critical facilities;
- the third level provides a specific definition of the assessment of the structural performance of the critical details, providing the effectiveness on the plant resilience of possible upgrading solutions, that aim at reducing the vulnerability, operating on the structure, or increasing the resilience, enhancing the method of interventions after the seismic damage.

Each level provides also a prioritization of facilities, based on the concept of Resilience Indicators (RI). The Resilience Indicators, from a practical perspective, scales the consequences of each facility to achieve a optimal resilience condition decided by the owner of the plant and defined through the break even point.
The Resilience Indicators allow to establish which facilities require in deep assessment from one step to the next.

Two case studies, representative of two actual industrial realities, a Steel Mill and a Chemical Plant, were carefully selected to apply and validate the proposed multilevel procedure. The Steel Mill is characterized by a huge in plan extension, and is characterized by drift sensitive facilities, easily to schematize as single degree of freedom structures. The Chemical Plant has a compact configuration that develops over the height; it is characterized by a

main braced building that support several vessels, mainly sensitive to peak floor acceleration.
The results of the detailed resilience assessment, applied on both the case studies, are used as a reference to validate the multilevel procedure.
The multilevel procedure provided results that well fit the detailed resilience assessment, regarding both resilience curve and the facilities prioritization. Furthermore, the convergence of results was achieved with a reduced number of steps.
Clearly, the application of the multilevel procedure strongly reduced the amount of detailed analyses, optimizing the in-field surveys and simplifying considerably the achievement of satisfactory results in terms of Plant's resilience.

List of Symbols and Abbreviations

ADRS	Acceleration Displacement Response Spectrum
$\mathbf{a_g}$	peak ground acceleration
β	logarithmic standard deviation
CBF	Concentrically Braced Frame
CIF	Critical Industrial Facilities
CCPS	Center for Chemical Process Safety
CMS	Conditional Mean Spectrum
C.O.V.	Coefficient Of Variation
CR	Complete Reconstruction
DL	Damage Limitation
DS	Damage State
EAL	Expected Annual Losses
$\mathbf{EAL_{s,i}}$	Expected Annual Loss associated with the i^{th} facility
$\mathbf{EAL_p}$	Expected Annual Loss of the whole Plant
$\mathbf{EAL_{iso}}$	Expected Annual Loss in the *iso-resilience* condition
$\mathbf{EAL_{cum}}$	Cumulative Expected Annual Loss
EMS	European Macroseismic Scale
EPRI	Electric Power Research Institute
EDP	Engineering Demand Parameter
$\mathbf{F_{a,max}}$	maximum horizontal force accounting for the seismic amplification over the height, according to VCI Guidelines
FRS	Floor Response Spectrum
FSD	First order Stochastic Dominance
γ	importance factor
g	acceleration of gravity

GA	Genetic Algorithm
IDA	Incremental Dynamic Analysis
IM	Intensity Measure
$\mathbf{I_v}$	Vulnerability index
λ	mean annual frequency of the seismic action
LPG	Liquified Petroleum Gas
LP-HC	Low Probability-High Consequences
LR	Loss of Resilience
LS	Limit State
MAF	Mean Annual Frequency
MECE	Mutually Exclusive and Collectively Exhaustive
MRF	Moment Resisting Frame
NC	Near Collapse
$\mathbf{P_f}$	Failure Probability
$\mathbf{P_{f,RS_i}}$	probability of exceedance of the ith resilience state
$\mathbf{P_{LS_i}}$	Probability of exceedance of the ith limit state
$\mathbf{q(t)}$	Residual functionality
QRA	Quantitative Risk Assessment
$\mathcal{R}$	Reconstruction schedule
R	Resilience
RC	Reinforced Concrete
REDI	Resilience-base Earthquake Design Initiative
RI	Resilience indicators
RS	Resilience State
$\hat{\sigma}$	Standard deviation
$\mathcal{S}$	Network system
$\mathbf{S_a(T_1)}$	spectral acceleration computed in correpsondance of the period T_1
SD	Severe Damage
SRC	Standard Regression Coefficient

SSD	Second order Stochastic Dominance
$\mathbf{T_a}$	Fundamental period of non-structural element
$\mathbf{t_{ave,i}}$	Average recovery time of the ith facility
$\mathbf{t_{BEP}}$	Break even point
$\mathbf{t_{ev}}$	Time at which a damage is triggered
$\mathbf{T_{insp}}$	Time for the inspection
$\mathbf{T_{LC}}$	Reference time
$\mathbf{T_{sm}}$	Time for the introduction of safety measures
$\mathbf{T_D}$	Time for the design of the intervention
$\mathbf{T_R}$	Time for demolition and econstruction
$\mathbf{t_{rec}}$	Recovery time
$\mathbf{T_{rep}}$	Time for the replacement
UHS	Uniform Hazard Spectrum
VaR	Value at Risk

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