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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
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
$EAL_{s,i}$	Expected Annual Loss associated with the i^{th} facility
EAL_p	Expected Annual Loss of the whole Plant
EAL_{iso}	Expected Annual Loss in the <i>iso-resilience</i> condition
EAL_{cum}	Cumulative Expected Annual Loss
EMS	European Macroseismic Scale
EPRI	Electric Power Research Institute
EDP	Engineering Demand Parameter
$F_{a,max}$	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
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
P_f	Failure Probability
P_{f,RS_i}	probability of exceedance of the i^{th} resilience state
P_{LS_i}	Probability of exceedance of the i^{th} limit state
$q(t)$	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
$S_a(T_1)$	spectral acceleration computed in correpondance of the period T_1
SD	Severe Damage
SRC	Standard Regression Coefficient

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

Contents

1	Statement of the problem	1
1.1	Introduction	1
1.2	Risk assessment of industrial plants: state of the art	6
1.3	Open problems	12
2	Objectives and methodology	17
2.1	Objectives	17
2.2	Methodology	18
3	Seismic Resilience assessment of Industrial Plants	21
3.1	The concept of resilience	21
3.2	Seismic resilience of inter-dependent facilities	23
3.2.1	Stand-alone facilities	24
3.2.2	Connected systems	28
3.3	A proposal for Resilience assessment of Industrial Plants	30
3.3.1	Stand-alone facilities	30
3.3.2	Interconnected systems	38
3.3.3	Definition of the risk metric	39
3.3.4	Practical example for the calculation of Resilience	40
3.3.5	Detailed Resilience assessment and facilities prioritization	43
4	The multilevel procedure	47
4.1	Organization of the multilevel procedure	47
4.2	Level 1	51
4.2.1	"Walk-down" and structural inspections	51
4.2.2	Analysis of the structural performance and simplified Models	55
4.2.3	Consequences matrix	56

4.3	Level 2	59
4.3.1	Assessment of the structural performance	60
4.3.2	Estimation of the consequences	61
4.4	Level 3	62
4.4.1	Analysis of the critical details	62
4.5	Optimization procedure	64
4.5.1	Break even point	65
4.5.2	Resilience indicators	66
4.5.3	Selection of the algorithm for the optimal resilience condition	74
5	The Steel Mill	77
5.1	Introduction	77
5.2	Description of the case study	77
5.2.1	The Plant configuration	77
5.2.2	Description of the facilities	78
5.3	Seismic hazard	88
5.4	Resilience Assessment	89
5.4.1	System network	90
5.4.2	Restoration schedule	91
5.4.3	Detailed Resilience assessment	91
5.4.4	Application of the multilevel procedure	106
5.5	Concluding considerations	121
6	The chemical Plant	125
6.1	Introduction	125
6.2	Description of the chemical plant	125
6.2.1	The Plant configuration	125
6.2.2	Description of the facilities	126
6.3	Seismic Hazard	130
6.4	Resilience assessment	134
6.4.1	System network	134
6.4.2	Restoration schedule	135
6.4.3	Detailed Resilience assessment	135
6.4.4	Application of the multilevel procedure	152
6.5	Concluding considerations	163
7	Conclusions and further developments	169
7.1	General conclusions	169
7.2	Further developments	172

A	Vulnerability assessment of the Steel Mill	175
A.1	Vulnerability assessment	175
A.1.1	Numerical models	175
A.1.2	Results of the vulnerability assessment	178
A.1.3	Water treatment unit	179
A.1.4	Additional alloys	184
A.1.5	Nitrogen argon vessels	198
References		204

List of Figures

1.1	The LPG tank farm at the Chiba refinery after the earthquake-triggered fires and explosions.	2
1.2	Collapse of the piperacks at the Tupras refinery after the Kocaeli earthquake.	2
1.3	Schematic representation of vulnerability, risk and resilience. .	5
1.4	Example of ALARP state space.	7
1.5	Loss curve and identification of the risk metrics (from Yoshikawa and Goda (2013)).	8
1.6	Example of industrial facilities.	11
3.1	Graphical meaning of a) resilience and b) loss of Resilience. ...	24
3.2	Different shapes of the recovery path: a) linear path, b) trigonometric path and c) exponential path. Readapted from Cimellaro et al. (2010a)	27
3.3	Constant recovery path.	33
3.4	Stepped recovery path.	33
3.5	Comparison of two loss of resilience equivalent conditions: a) characterized by partial Residual functionality for a longer time; b) characterized by complete loss of functionality for a shorter time.	36
3.6	Graphical interpretation of the estimation of the resilience curve.	37
3.7	Adoption of the event tree for the estimation of the resilience curve.	38
3.8	Comparison of the resilience curve of two facilities, respectively characterized by low and high vulnerability.	40
3.9	Recovery paths considering different dependencies among facilities and different restoration schedule.	41

4.1	Framework of the multilevel procedure.	48
4.2	Interaction between the Plant's technical office and the Engineers' team for the level 1.	49
4.3	Interaction between the Plant's technical office and the Engineers' team for the level 2.	50
4.4	Framework for the extended methodology (the RBI methodology is indicated by the dashed line). Readapted from Selvik et al. (2011).	52
4.5	Hyperbolic relationships among R - t_{rec} - q	58
4.6	Example of detailed assessment by means of the sub-structuring method.	63
4.7	Case 1: definition of the EAL of the Plant, in the case of series restoration schedule (a plant constituted of 4 facilities belonging to different units connected in series is considered). .	68
4.8	Case 2: definition of the a) resilience curve and the b) cumulated EAL of the Plant, in the case of parallel restoration schedule (a plant constituted of 4 facilities belonging to different units connected in series is considered).	69
4.9	Comparison of four different shaped resilience curve, but characterized by the same EAL.	70
4.10	Example of three resilience curve for the application of the stochastic dominance criteria (the lognormal scale is adopted for the x axis for a better comparison at low frequencies).	72
4.11	Example of iso-resilience condition.	74
5.1	Planimetry of the steel mill.	79
5.2	Side views of the main building steel wharehouse: the spacing among each bay is variable between 16 and 18 meters; top: X direction; bottom: Y direction.	80
5.3	Plan configuration of the bracing system.	81
5.4	Section adopted for the columns.	81
5.5	Mud container: original drawings and assembly.	82
5.6	Original drawings of the support 1.	83
5.7	Original drawings of the support 2.	84
5.8	Original drawings of the silos.	84
5.9	Shop drawings of the additional alloys unit.	85
5.10	Schematic drawings of the silo 1.	86
5.11	Silo 2 (additional alloys storage)	86
5.12	Overview of the four silos and disposition of the pipelines	87
5.13	Seismic hazard map and identification of the area of interest in which the Steel Mill is considered.	88
5.14	Seismic hazard curve considered for the steel mill.	89
5.15	Uniform hazard spectra considered for the steel mill.	89

5.16	Block diagram of the steel mill.	90
5.17	Resilience curve: a) lognormal plot, B) standard plot.	102
5.18	Cumulated EAL: a) lognormal plot, B) standard plot.	103
5.19	Distribution of the EAL and its lognormal fit.	104
5.20	SRC parameters for the steel mill (for the numbering see table 5.5).	104
5.21	Resilience curve of the five units and the whole Plant.	110
5.22	Comparison of the cumulated EAL obtained from the three resilience curves.	112
5.23	Resilience curves obtained from the three scaling conditions. . .	117
5.24	Comparison of the resilience curves obtained applying the detailed and the multilevel procedures.	122
6.1	First storey (+6.00 m).	126
6.2	Second storey (+12.00 m).	127
6.3	Third storey (+17.00 m).	127
6.4	Side view: alignment 1.	128
6.5	Side view: alignment 2.	128
6.6	Side view: alignment 3.	129
6.7	Side view: alignment A.	129
6.8	Side view: alignment B.	129
6.9	Side view: alignment C.	130
6.10	Side view: alignment D.	130
6.11	Seismic hazard map and identification of the area of interest in which the chemical plant is considered.	131
6.12	Uniform hazard spectra for the chemical plant.	132
6.13	Hazard curve for the chemical plant.	132
6.14	Block diagram of the chemical plant.	134
6.15	Tension and compression behaviour adopted for the lumped plasticity approach proposed by the FEMA 356 (2000) and Hamburger et al. (2012).	138
6.16	Response spectra, unscaled and matched for the E-W direction.	141
6.17	Response spectra, unscaled and matched for the N-S direction.	142
6.18	Response spectra, unscaled and matched for the vertical direction.	143
6.19	Resilience curve and its confidence bounds (16% and 84% quantile) used for the estimation of the EAL of the chemical plant.	151
6.20	Distribution of the EAL and lognormal fit for the chemical plant.	151
6.21	Distribution of the SRC ranks over the main building and the 21 vessels.	152
6.22	Floor response spectra at the first level, along the x direction. . .	156

6.23	Floor response spectra at the second level, along the x direction.	158
6.24	Floor response spectra at the third level, along the x direction. .	158
6.25	Resilience curve of the plant at the first level (units are the macro-areas reported in table 6.2).	160
6.26	Comparison of the resilience curves obtained applying the detailed and the multilevel procedures.	164
6.27	Floor response spectra of the first floor: detailed calculation versus EN1998:1 ($z/H = 0.350$).	166
6.28	Floor response spectra of the second floor: detailed calculation versus EN1998:1 ($z/H = 0.70$).	167
6.29	Floor response spectra of the third floor: detailed calculation versus EN1998:1 ($z/H = 1$).	167
7.1	comparison of the resilience curves obtained applying the detailed and the multilevel procedures - chemical plant.	171
7.2	comparison of the resilience curves obtained applying the detailed and the multilevel procedures - steel mill.	171
A.1	detailed modelling of the additional alloys unit.	176
A.2	simplified modelling of the silos of the additional alloys unit. .	177
A.3	capacity curves of the mud container.	180
A.4	capacity curves comparison of the mud container and the support structure: the sudden stiffness and resistance change at the elastic limit of the capacity curve of the mud container is due to a local instability of the compressed flange of the supporting leg.	182
A.5	ABAQUS model and results at the plastic deformation at the elastic limit.	182
A.6	capacity curves and related limit states of the sand filters.	185
A.7	capacity curves of the silo 1 (additional alloys unit) along the X and Y direction.	186
A.8	capacity curves of the silo 1 (additional alloys unit) along the X and Y direction.	188
A.9	capacity curve of the supporting tower.	191
A.10	capacity curves of the BC 1 (additional alloys unit) along the X and Y direction.	196
A.11	capacity curves of the BC 2 (additional alloys unit) along the X and Y direction.	197
A.12	capacity curves of the dust filter (additional alloys unit) along the X and Y direction.	200

List of Tables

3.1	Literature review about resilience definition	23
3.2	Coefficient of variation for the recovery time phases (readapted from Almufti and Willford (2013) and Lin and Wang (2017b)).....	28
3.3	Quantitative meaning of the Resilience states in terms of recovery time and residual functionality.	35
4.1	Quality rating of design requirements, and the associated dispersion β , as per FEMA P-695 (2009).....	57
4.2	Example of consequence matrix	60
4.3	Matrix of the Resilience indicators	67
5.1	Characteristics and mean values of the structural materials used for the vulnerability assessment of the two case studies. ...	92
5.2	Summary of the results of the detailed vulnerability assessment.	93
5.3	Quantitative meaning of the Resilience states in terms of recovery time and residual functionality.....	95
5.4	Summary of the estimated consequences (days) for each resilience state: the number out of brackets represents the recovery time, the number between brackets represents the residual functionality.	95
5.5	ID of the facilities belonging to the steel mill	105
5.6	Summary of the results of the simplified vulnerability assessment.	113
5.7	Possible strategies for the application of level 2 and 3 of the multilevel procedure.	114
5.8	Consequences estimated in a simplified way a fraction of the total reconstruction time; the values reported between brackets refers to the residual functionality.....	115

5.9	Definition of the resilience indicators (RI) adopting the optimized scaling procedure. The colored filling refers to the importance level: the lower is the resilience indicator the more the structure is critical. The number between brackets represents the ranking based on the R.I.	116
5.10	Resilience indicators after the second step.....	119
5.11	Resilience indicators after the third iteration.	120
5.12	EAL, expressed in days of shut down, obtained from the application of the detailed approach and the multilevel procedure.	122
6.1	Main characteristics of the vessels and additional informations about the main structure-to-vessels connections. The bolts are equal for each bolted connection of the vessel.	133
6.2	Macro-areas used for the definition of the <i>optimal restoration schedule</i>	135
6.3	Characteristics and mean values of the structural materials used for the vulnerability assessment of the two case studies. . .	136
6.4	List of the 20 real accelerograms selected from the PEER database.	140
6.5	Vulnerability index and parameters for the definition of the fragility curves of the main structure.	144
6.6	Mean value and standard deviation for the estimation of the fragility curves of the vessels, adopting the detailed assessment (T_1 refers to the period of the principal modal shape of the peak floor acceleration sensitive components).	145
6.7	Vulnerability indexes and failure mechanism of the vessels. ...	146
6.8	Quantitative meaning of the Resilience states in terms of recovery time and residual functionality.	148
6.9	Vulnerability index and parameters for the definition of the fragility curves of the main structure; T_1 is equal to 0.23 s	156
6.10	Results of the simplified vulnerability analysis of the vessels, performed for the first level.	157
6.11	Results of the vulnerability assessment of the vessels investigated with detailed procedure at the second level.	157
6.12	Consequences estimated with a the simplified approach of the consequence matrices.	158
6.13	RI of the chemical plant after the application of the first step. .	159
6.14	RI of the chemical plant evaluated at the second step (first iteration on the second level) of the multilevel procedure.	161

6.15 EAL, expressed in days of shut down, obtained from the application of the detailed approach and the multilevel procedure.	163
A.1 comparison of the coupled versus the uncoupled modelling approach.	177
A.2 masses considered for the seismic vulnerability assessment. ...	179
A.3 Vulnerability indexes for the superstructure of the mud container, assuming a fundamental period T_1 equal to 0.297 s (the structure is symmetric, therefore the fundamental period along the two principal directions is equal).	181
A.4 Vulnerability indexes for the support 1, assuming a fundamental period $T_{1,x}^*$ and $T_{1,y}^*$ equal to 0.28 s.	183
A.5 Vulnerability indexes for the support 2, assuming a fundamental period $T_{1,x}^*$ and $T_{1,y}^*$ respectively equal to 0.31 s and 0.34 s.	184
A.6 Vulnerability indexes for the sand filters, assuming a fundamental period T_1 s.	185
A.7 Vulnerability indexes silo 1 (additional alloys unit), assuming a fundamental period $T_{1,x}^*$ and $T_{1,y}^*$ respectively equal to 3.96 s and 4.00 s.	189
A.8 limit states for the braces in tension according to EN 1998-3 (2005)	190
A.9 Vulnerability indexes silo 2 (additional alloys unit), assuming a fundamental period $T_{1,x}^*$ and $T_{1,y}^*$ respectively equal to 0.35 s and 0.61 s.	190
A.10 limit states for the braces in tension according to EN 1998-3 (2005)	191
A.11 Vulnerability indexes of the supporting tower (additional alloys unit), assuming a fundamental period $T_{1,x}^*$ and $T_{1,y}^*$ respectively equal to 0.97 s and 1.51 s.	192
A.12 Vulnerability indexes for the BC1 (additional alloys unit).	194
A.13 Vulnerability indexes for the BC2 (additional alloys unit).	195
A.14 Vulnerability indexes for the nitrogen argon vessels.	199
A.15 Vulnerability indexes of the dust filters, assuming a fundamental period $T_{1,x}^*$ and $T_{1,y}^*$ respectively equal to 0.85 s and 0.83 s.	201
A.16 Vulnerability indexes of the dust filters, assuming a fundamental period $T_{1,x}^*$ and $T_{1,y}^*$ respectively equal to 0.36 s and 0.80 s.	203