EC Collaborative Project SILER: Seismic-Initiated events risk mitigation in LEad-cooled Reactors

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TRAINING COURSE ON SEISMIC PROTECTION OF LEAD-COOLED REACTORS

SEISMIC FRAGILITY ANALYSIS OF ISOLATED NPPs

Federico Perotti
Department of Structural Engineering
Politecnico di Milano
The evolution of the “risk picture” in NPPs

The risk related to “internal events” has decreased of 2-3 orders of magnitude

“external events” dominate the risk
Seismic fragility of a component is defined as its probability of failure conditioned to the severity of the ground motion.

Seismic hazard $\times$ fragility $\equiv$ seismic risk

(at the component level)

site property component property
Topics

Main topic: numerical procedures for evaluating fragility of structural and/or equipment components

But: problems related to the definition of hazard and seismic input will be enlightened
Seismic fragility: traditional approach

- Selection of safety-related structural elements
- Identification of the more significant failure modes

\[ A = \bar{A} \cdot \varepsilon_R \cdot \varepsilon_U \]

\( \bar{A} \) mean ground acceleration capacity

\( \varepsilon_R \) inherent randomness

\( \varepsilon_U \) epistemic uncertainty

\( \varepsilon_R, \varepsilon_U \) random variables lognormally distributed with logarithmic standard deviation \( \beta_R \) and \( \beta_U \)

Development of fragility curves reduced at estimation of 3 parameters \( \bar{A}, \beta_R, \beta_U \)

Analyses
+ Engineering judgment
+ Available test data

Fragility analysis of isolated NPPs
Seismic fragility: traditional approach

Estimation of parameters accomplished by:

- numerical analyses
- *engineering judgment*
- available test data

large deal of uncertainty

contribution to seismic risk very large
Seismic fragility: needs for improvement

We need more rigorous methodologies for a more accurate and rational estimation of fragilities,

• in order to reduce as much as possible all the uncertainties arising from analyst’s lack of knowledge about models, methods for response analysis, limit-state formulation, etc..

• for a more accurate estimation of sensitivities, i.e. for improving the feedback on design
Probability of failure: PEER approach

\[ P_f = \iint P \{ DM > dm_f \mid EDP = edp \} \]

“Total probability” theorem

\[ \cdot p_{EDP}(edp \mid IM = im) \]

\[ \cdot p_{IM}(im)d(edp)d(im) \]

DM Damage Measure from equipment designer

\((dm_f\) damage at failure)\n
EDP Engineering Demand Parameter from structural designer

IM Intensity Measure (annual extreme) from seismic hazard expert
Seismic fragility of a component

\[ F(dm, im) = P\{DM > dm \mid IM = im\} = \]
\[ \int P\{DM > dm \mid EDP = edp\} \cdot p_{EDP}(edp \mid IM = im) \, d(edp) \]

\( F(dm, im) \) is the component fragility, to be supplied to the system analyst for the computation of overall plant fragility.
**Simplified approach:** failure criterion directly in terms of an Engineering Demand Parameter

\[
P_f = \int P\left\{ EDP > edp_f \mid IM = im \right\} p_{IM}(im) \, d(im)
\]

\[
F(edp, im) = P\left\{ EDP > edp \mid IM = im \right\}
\]

*fragility function*

*Here:* $EDP =$ extreme value $a$ of absolute acceleration or relative displacement $u$

$IM =$ PGA ($a_g$) of most severe component of horizontal ground motion
Linear system: traditional building

limit state function (in terms of structural amplification)

\[ \tilde{g}(X, R, a, a_g) = \frac{a}{a_g} - R(X) = 0 \]

- \( X \) is the vector of random variables listing dynamic properties of the building/ground system and excitation control parameters
- \( R \) is a random variable accounting for variability of the dynamic response due to seismic input randomness
- \( R \) is strongly correlated to variables in \( X \)
- by exploiting linearity, the analysis must not be repeated for increasing \( a_g \)
Criteria for fragility computation

Toolbox for fragility analysis

- Two-stage analysis of the building/component system
- FE linear analysis of the reactor building
- Simplified soil-structure analysis
- Simulation method to account for random loading
- Response Surface Method for modelling the influence of the random parameters on the seismic response
- Level II reliability analysis for refining the Response Surface
- Monte Carlo analysis to compute the final probability of failure
Solution of the random vibration problem

\[ \tilde{g}(X, R, a, a_g) = \frac{a}{a_g} - R(X) = 0 \]

\( R(X) \) is a random variable whose realization \( r(X) \) is the extreme value of support acceleration conditioned to the values of the random variables in \( X \), i.e.:

\[ \mu_R = \mu_R(X) \quad ; \quad \sigma_R = \sigma_R(X) \]

for each realization of \( X \) a random vibration problem must be solved (here by simulation) to get the mean and standard deviation of \( R \)
Response Surface Methodology

To model the correlation between $R$ and the other RVs an analytical formulation can be sought in the following form (dual Response Surface Methodology):

$$
\mu_R(X) = \sum_{i=1}^{m} a_i z_i(X) + \varepsilon_\mu \quad ; \quad \sigma_R(X) = \sum_{i=1}^{m} b_i z_i(X) + \varepsilon_\sigma
$$

where the $z_i$ are usually polynomial functions, the $a_i$ are coefficients to be determined and where two error terms have been introduced.
Building the RS via numerical experiments

- an experimental design is chosen,
- at each experimental point a sample of ground motion realizations is generated, according to the parameters in $X$
- the extreme value of $R$ is computed for each realization and the mean and variance of $R$ are estimated
- the procedure is repeated for all experimental points, leading to $n$ observed values for mean and variance
- the coefficients of the two Response Surfaces are computed by the least square method.
- the error terms variance is estimated via residual analysis
Computation of $P_f$ via Monte Carlo simulation

Once the RS, and thus the limit state function, are defined the fragility, here defined as probability of exceeding a given structural amplification, can be obtained by Monte Carlo evaluation of the integral:

$$F(a, a_g) = P_{exc}(a / a_g) = \iiint_{\tilde{g} < 0} p_R(r, x) dr \, dx$$

NOTE: even though the limit state function can be evaluated only once (for linearity), the integral must be computed for each amplification value
Probability of failure: simplified/linearized

If the system is linear, once fragility is obtained in terms of structural amplification, to compute the risk \( P_f \):

\[
P_f = \int F(edp, im) p_{IM}(im) \, d(im) = \\
= \int P_{exc}(a_f / a_g) p_{Ag}(a_g) \, d(a_g) = \\
= P_f(a_f)
\]

NOTE: \( a_g \) is the yearly extreme, the annual probability of failure is delivered
Example: IRIS project - reactor building

Computation of the fragility of a component inside the vessel

\[ EDP \quad \text{absolute horizontal acceleration } "a" \]
\[ \text{at reactor coolant pumps level} \]
\[ a_f = 25 \, m/s^2 \, (\text{from } HCLPF=0.5 \, g) \]
Example: criteria for fragility analysis

- **Finite Element (shell only) modelling of the building**
- **Simplified modelling of vessel and containment**
- **Simplified soil-structure interaction modelling**
- **Dynamic analysis via modal superposition (one modal extraction for each experimental point)**
- **Damping model in terms of modal factors**
- **Seismic input from deterministic response spectrum (Eurocode 8.1 for soil type C and event type 1)**
- **Random variables: soil damping, soil elastic modulus, vessel damping**
Example: fragility curve

Fragility in terms of structural amplification

\[ P_{exc} \left( \frac{a_f}{a_g} \right) \]

mean amplification equal to 3.1
Example: seismic hazard

Seismic hazard in terms of PGA vs return period $T$ (northern Italy site with low-to-intermediate seismicity)

$$PGA = 0.32 \, g$$

$$T = 10000 \, yrs$$

From $T(a_g)$ the distribution function of the yearly PGA extreme value can be derived

$$P_{A_g}(a_g) = 1 - \frac{T(a_{g,\text{min}})}{T(a_g)}$$
Example: risk computation

\[ P_f = \int P_{\text{exc}}(a_f / a_g) p_{A_g}(a_g) \, d(a_g) \]

**result:** \( P_f = 5.1 \times 10^{-6} \)

PGA range for RS refinement
Problems related to hazard

The definition of hazards at the site is extended to return periods being far beyond the available “historical data range”. This probabilistic description is not reliable. Can be used for:

• comparing different solutions
• obtaining qualitative information on PGA ranges important for risk evaluation

For other purposes we need to add more physical information (scenario analyses?)
Fragility of isolated reactor buildings

Example: IRIS NSSS building with seismic isolation

The use of High Damping Rubber Bearings has been investigated

HDRB device

Flood level (1 m)

1 m gap

1 m thick

22 m

21 m

23 m

56 m

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Fragility analysis of isolated NPPs
Isolated building example: IRIS reactor

Design criteria

• about 100% shear deformation at SSE, resulting in limited relative displacement (order of 10-15 cm)
• no tension forces on isolators at SSE
The safety analysis of the isolated building

The accelerations inside the building drop to low values so that seismic risk is likely to be entirely related to the behaviour of the isolation system. In such situation:

• the (non-linear) mechanical behaviour of the isolators will govern the dynamic response
• the randomness of the isolators mechanical properties will govern the response variability
• the deformation capacity of the isolators will govern the building collapse
Isolated building: failure in terms of excessive shear deformation of the isolators

failure: exceedance of a limit relative displacement

\[ F(\text{edp}, \text{im}) = P\left\{ U > u \mid A_g = a_g \right\} = P_{\text{exc}}(u, a_g) \]

EDP is now the maximum relative horizontal displacement of an HDRB device

\[ g(X, u, a_g) = C - D(X, a_g) = u - U(X, a_g) = 0 \]

limit state function

NB: computation must be repeated for all PGA values given the system non-linearity
Fragility under stochastic loading

\[ g(X, u, a_g) = C - D(X, a_g) = u - U(X, a_g) = 0 \]

\( U(X) \) is a random variable whose realization \( u(X) \) is the extreme value of relative displacement conditioned to the values of the random variables in \( X \), i.e.:

\[ \mu_U = \mu_U(X) \quad ; \quad \sigma_U = \sigma_U(X) \]

for each realization of \( X \) a random vibration problem must be solved (here by simulation) to get the mean and standard deviation of \( U \)
Response Surface Methodology

To model the correlation between $U$ and the other RVs an analytical formulation can be sought in the following form (dual Response Surface Methodology):

$$
\mu_U (X) = \sum_{i=1}^{m} a_i z_i (X) + \varepsilon_\mu ; \quad \sigma_U (X) = \sum_{i=1}^{m} b_i z_i (X) + \varepsilon_\sigma
$$

where the $z_i$ are usually polynomial functions, the $a_i$ are coefficients to be determined and where two error terms have been introduced.
Computation of $P_f$ via Monte Carlo simulation

Once the RS, and thus the limit state function, are defined the fragility, here defined as probability of exceeding a
Given relative displacement, can be obtained by Monte Carlo evaluation of the integral:

$$F(u, a_g) = P_{exc}(u, a_g) = \int\int\int_{g<0} p_U(u, x) du \, d\mathbf{x}$$

NOTE: in the non-linear case the RS estimation and the integral evaluation must be repeated for each value of the PGA
Computation of risk at a given site

Once fragility is computed, to compute the risk $P_f$:

$$P_f = \int F(edp, im)p_{IM}(im) d(im) = \int P_{exc}(u_f/a_g)p_{Ag}(a_g) d(a_g) = P_f(u_f)$$

NOTE: $u_f$ is the relative displacement at failure.
The definition of the seismic hazard at the site is needed. If $a_g$ is the yearly extreme, the annual probability of failure is delivered.
Isolated building: failure defined in terms of excessive shear deformation of the isolators

Problems

• difficult to define failure for an isolation systems
• difficult to state relative displacement at failure for an isolation device (testing is complex with very large isolators)
• criterion is independent of the axial load, which varies very significantly under seismic actions
Isolated building: failure defined in terms of limit state domain under 3D forces

Tentative solution: failure $\rightarrow$ first damage

- look at first damage, defined as the attainment of limit stress at the steel-rubber interface ("OSID-type" Onset of Significant Inelastic Deformation)
- in the example here shown the stress at 400% shear strain under static load was taken as tentative limit stress (a more refined approach will be investigated after experimental activity)
- define limit state domain in terms of horizontal and vertical forces on the isolator
Isolated building: alternative “failure” formulation related to first damage

failure: exceedance of a “first damage” domain

\[ F(edp, im) = P\{edp > edp_f \mid A_g = a_g \} = P_{exc} (edp, a_g) \]

engineering demand parameter

\[ edp = \frac{SC}{SL} ; \quad edp_f = 1 \]

limit state function

\[ g(X, edp, a_g) = 1 - \frac{SC(X, a_g)}{SL(X, a_g)} \]
Proposed steps for fragility analysis

1. Experimental tests of the HDRB devices up to failure
2. Development of a refined FE model of the isolator
3. Statement of the limit state condition
4. Calibration of a simple hysteretic model for dynamic analysis
5. Performance of the fragility analysis for the isolating system according to a simplified dynamic model of the building and to the hysteretic model (4) of the isolator

+ fragility analysis of the equipments inside the building to be performed as for not isolated (mainly for vertical motion)
Fragility analysis of the isolators

Simplified modelling of isolators (from Abe et al 2004)

\[ F = F_1 + F_2 + F_3 \]

\[ F_1 = K_1 \left( \beta + (1 - \beta) \exp \left( - \frac{U_{\text{max}}}{\alpha} \right) \right) U \]

\[ + a \left[ 1 - \exp(-b|U|) \right] \text{sgn}(U) \]

\[ \dot{F}_2 = \frac{Y_t}{U_t} \left\{ \dot{U} - \left| \frac{F_2}{Y_t} \right|^n \text{sgn} \left( \frac{F_2}{Y_t} \right) \right\} \]

\[ Y_t = Y_0 \left( 1 + \frac{U}{U_H} \right)^p \]

\[ U_t = U_0 \left( 1 + \frac{U_{\text{max}}}{U_S} \right) \]

\[ F_3 = K_2 \left| \frac{U}{U_H} \right|^r U \]

Multiaxial Behaviors of Laminated Rubber Bearings and Their Modeling. II: Modeling

Masato Abe, M.ASCE\(^1\); Junji Yoshida\(^2\); and Yozo Fujino, M.ASCE\(^3\)

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Simplified model calibration

Results of cyclic test (from ENEA)

experimental
numerical

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Fragility analysis of the isolators

Details on hysteresis cycles

(2° cycle) (3° cycle)
### Fragility analysis of the isolators

#### Equivalent damping and secant stiffness

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Experimental Equivalent Viscous Damping Factor [%]</th>
<th>Experimental Reference Stiffness [KN/mm]</th>
<th>Numeric Equivalent Viscous Damping Factor [%]</th>
<th>Numeric Reference Stiffness [KN/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1° cycle</td>
<td>17</td>
<td>0.45</td>
<td>24</td>
<td>0.43</td>
</tr>
<tr>
<td>2° cycle</td>
<td>15</td>
<td>0.35</td>
<td>16</td>
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<tr>
<td>3° cycle</td>
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<td>12</td>
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<td>4° cycle</td>
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<td>10</td>
<td>0.48</td>
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<tr>
<td>5° cycle</td>
<td>14</td>
<td>0.60</td>
<td>7.2</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Fragility analysis of the isolators

Simplified non-linear modelling of the isolated building

Hypotheses and criteria:
• building above isolators behaves as a rigid body
• horizontal restoring forces in isolators are modeled according to a simplified hysteretic model
• vertical restoring forces in isolators are linear elastic with no interaction with horizontal ones
Example of performance of fragility computation

- failure in terms of “first damage” limit state
- random parameters are the two variables defining the failure condition (parabola) and two variables roughly defining overall stiffness and dissipation in the non-linear model of the isolator
Fragility (and “prototype” risk) analysis of the isolators

Results of fragility computation and risk assessment for prototype site

\[ P_f \] vs. \[ a_g [g] \]

\[ P_f^* P_{ag} (a_g) \] vs. \[ a_g (m/s^2) \]

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Fragility analysis of isolated NPPs
Open questions (beyond hazard)

*seismic input modelling*

artificial spectrum-compatible accelerograms have been here used; this is not satisfactory; some aspects related to input motion must be investigated with reference to the need of isolated buildings analysis.
Open questions

seismic input modelling

Effects of spatial variation of seismic motion:

• **vertical motion** s.v. induces rocking motion; there are very good studies mostly related to building response (isolation efficiency), but the effect on isolators, especially in terms of vertical load variation, must be still investigated

• the effect of **horizontal motion** s.v. on relative displacement across isolators needs attention
Open questions

**seismic input modelling**

- We need information on *correlation* between vertical and horizontal components (assumed to be null in most studies)
- *Embedment* effects need attention

*a deeper physical insight on seismic input is needed*
Open questions

*structural modelling* is generally not tailored to the level of excitation which are important for risk

- we need to develop better models of the *isolators behavior*, accounting for vertical force variation and for 2D motion in horizontal plane; must be reliable at very high deformation levels
- we need to investigate *isolators failure*
Open questions

*structural modelling*

response analysis for vertical response (not affected by isolation) must be based on better models, in terms of

• *isolators behavior* (coupling with horizontal, large axial force variation …)

• *reinforced concrete structures*, developing “mildly non-linear” behaviour, usually modelled with very crude assumption (*general issue*)