The use of Nonlinear Static Procedures for seismic assessment of structures

Rui Pinho
Several Nonlinear Static Procedures available…

- **Capacity Spectrum Method (CSM)** (Freeman, 1975; ATC-40, 1996)
- **N2 Method (N2)** (Fajfar and Fischinger, 1988; EC8, 2005; OPCM-3274)
- **Displacement Coefficient Method** (FEMA 273, 1997)
- **Multimodal Pushover Analysis (MPA)** (Chopra and Goel, 2001)
- **Incremental Response Spectrum Analysis (IRSA)** (Aydinoglu, 2004)
- **Adaptive Modal Combination Procedure (AMCP)** (Kalkan and Kunnath, 2006)
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- **Advanced Capacity Spectrum Method** (Elnashai and Gentcurk, 2008)
- **Generalized Multi-mode Pushover Analysis** (Sucuoglu, 2009)

etc, etc..

Overall, how do they fair against each other?..
Main difference in terms of capacity estimation is the used of adaptive or non-adaptive pushover
In some cases, (displacement-based) adaptive pushover may be advantageous.
## Case-studies: 2D buildings (RC or steel, old or new)

### 16 buildings

(regular & irregular; different materials and design type)

<table>
<thead>
<tr>
<th>Material</th>
<th>Seismic Design</th>
<th>Analyses</th>
<th>Analysed frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Designed</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td>Medium / High ductility</td>
<td>6</td>
</tr>
<tr>
<td>Designed</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>Designed</td>
<td>Weak / non-weak 1st floor</td>
<td>5</td>
</tr>
</tbody>
</table>

*Case-studies: 2D buildings (RC or steel, old or new)*
Case-studies: 2D buildings (RC or steel, old or new)

E.g.: edifici esistenti, edifici rinforzati con FRP, ecc

<table>
<thead>
<tr>
<th>Steel bars</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_y = 414$ MPa</td>
<td>$f_{cu} = 30-33$ MPa</td>
</tr>
<tr>
<td>$E_s = 210000$ MPa</td>
<td>$\varepsilon_{cu} = 0.0022$</td>
</tr>
<tr>
<td>$E_s/E_f = 0.009$</td>
<td>$\varepsilon_{cu} = 0.0035$</td>
</tr>
</tbody>
</table>

**2nd case study** $f_{cu} = 33$ MPa

**Beam cross-section**

**Column cross-section**

**3rd case study** $f_{cu} = 33$ MPa

**Beam cross-section**

**Column cross-section**

Figure 1: frame structures: geometry and beam / column cross-sections.

E.g.: edifici esistenti, edifici rinforzati con FRP, ecc
Case-studies: 2D buildings (RC or steel, old or new)

(From Ohtori et al. 2000)
3D Buildings – one example: SPEAR frame
Masonry buildings
8 continuous deck bridges
(2 types of abutments: labeled A/B)

A continuous deck-abutment connections supported on piles
(bilinear behaviour)

B deck extremities supported on pot bearings
(linear behaviour)
Table 1. Employed set of records

<table>
<thead>
<tr>
<th>Name</th>
<th>Earthquake</th>
<th>Duration</th>
<th>Significant Duration</th>
<th>PGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA 02</td>
<td>1940, ElCentro</td>
<td>39.38 s</td>
<td>26.5 s</td>
<td>0.68 g</td>
</tr>
<tr>
<td>LA 04</td>
<td>Imperial Valley, 1979</td>
<td>39.38 s</td>
<td>15 s</td>
<td>0.49 g</td>
</tr>
<tr>
<td>LA 06</td>
<td>Imperial Valley, 1979</td>
<td>39.38 s</td>
<td>14 s</td>
<td>0.23 g</td>
</tr>
<tr>
<td>LA 08</td>
<td>Landers, 1992</td>
<td>79.98 s</td>
<td>34 s</td>
<td>0.43 g</td>
</tr>
<tr>
<td>LA 10</td>
<td>Landers, 1992</td>
<td>79.98 s</td>
<td>33 s</td>
<td>0.36 g</td>
</tr>
<tr>
<td>LA 12</td>
<td>Loma Prieta, 1989</td>
<td>39.98 s</td>
<td>15 s</td>
<td>0.97 g</td>
</tr>
<tr>
<td>LA 14</td>
<td>Northridge, 1994</td>
<td>59.98 s</td>
<td>15 s</td>
<td>0.66 g</td>
</tr>
<tr>
<td>LA 16</td>
<td>Northridge, 1994</td>
<td>14.945 s</td>
<td>14.945 s</td>
<td>0.58 g</td>
</tr>
<tr>
<td>LA 18</td>
<td>Northridge, 1994</td>
<td>59.98 s</td>
<td>15 s</td>
<td>0.82 g</td>
</tr>
<tr>
<td>LA 20</td>
<td>Palm Springs, 1986</td>
<td>59.98 s</td>
<td>15 s</td>
<td>0.99 g</td>
</tr>
</tbody>
</table>
2D NSP comparison – Building type results

- Best response estimates and lower scatter levels obtained for concrete seismically designed buildings

- Seismically non-designed buildings with the highest differences between NSPs
Overall comparisons

- All NSPs are able to predict displacement response with relatively good accuracy
Overall observations

- All four NSPs proved to be able to predict displacement response with relatively good accuracy (for all sorts of bridge configurations: regular, irregular, short, long)

  Reassurance regarding the use of such methodologies for assessing response displacements and deformations

- On the other hand moments and shear forces were typically underestimated by at least 20-30%

  Further developments in force prediction, using NSPs, are conspicuously needed

- Difficulty in recommending a single NSP over the rest (respective performances not consistent throughout all response parameters)

  Simply a question of personal preference, perhaps..
- Based on EC8 (hence employs N2)

- Proposes two distributions; principal and secondary

- Assigns limits of applicability to such distributions (based on modal mass participation and period of vibration)

- Does not include commentaries nor other background information to justify its rules
Characteristics of load distributions

• Proportional to 1st Mode

\[ F_i = F_b \frac{m_i \Phi_i}{\sum (m_j \Phi_j)} \text{ dove: } F_b = S_D(T) \cdot \frac{W}{g} \lambda \]

• Proportional to equivalent static forces:

\[ F_i = F_b \frac{z_i \cdot W_i}{\sum (z_j W_j)} \text{ dove: } F_b = S_D(T) \cdot \frac{W}{g} \lambda \]

• Proportional to modal storey shears
Characteristics of load distributions

Secondary Distribution

• Uniform:

\[ F_i = F_b \cdot \frac{m_i}{\sum m_j} \]

dove: \[ F_b = S_D(T) \cdot \frac{W}{g} \lambda \]

• Adaptive

(displacement- or force-based?)
Examples of applicability limits

Proportional to equivalent static

+ Uniform

\[ m\% \geq 75\% \]
Examples of applicability limits

Proportional to equivalent static

\[ m\% \left( T_1 \right) \geq 75\% \]

Modal storey shears

\[ T_1 \geq T_c \]
<table>
<thead>
<tr>
<th>SLC</th>
<th>N° elementi non verificati</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DISTRIBUZIONE</strong></td>
<td><strong>FRAGILI</strong></td>
</tr>
<tr>
<td>Pari ai tagli di piano (da analisi lineare)</td>
<td>28</td>
</tr>
<tr>
<td>Proporzionale alle forze statiche</td>
<td>31</td>
</tr>
<tr>
<td>Proporzionale al 1° modo</td>
<td>31</td>
</tr>
<tr>
<td>Proporzionale alle masse (uniforme)</td>
<td>31</td>
</tr>
<tr>
<td>Adattiva in spostamento (DAP)</td>
<td>34</td>
</tr>
<tr>
<td><strong>Dinamica non lineare:</strong></td>
<td>35 (36)</td>
</tr>
</tbody>
</table>

\[ T_1 = 1,53 \text{ s} \quad \leftrightarrow \quad m\% \approx 80 \% \]

\[ T_C (SLC) = 0,70 \text{ s} \]

\[
\begin{align*}
T_1 & > T_C \\
m\% & > 75 \%
\end{align*}
\]
$T_1 = 1,06s \quad m\% \approx 77 \%$

$T_C (SLC) = 0,70s$

$T_1 > T_c \quad m\% > 75 \%$
• Storey shear distribution seems inadequate;

• Applicability limits \((T_1 > T_C, \ m\% > 75\%)\) seem unfounded;

• Distributions proportional to equivalent static forces and (displacement-based) adaptive pushover seemed to lead to best results;

• Further case-studies are conspicuously needed (only 5 considered until now);

• However, the most important thing would perhaps be for the (Italian) code to provide background information and commentaries on its rules