EC-8 vs IBC through the actual design of two seismic isolated projects

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Structural Engineer
Outline

1. Introduction
2. Buildings description
   a. Onassis Cultural Center (OCC)
   b. SNF Cultural Center (SNFCC)
3. Seismic design requirements
4. Seismic analyses
5. Differences between IBC and EC8
6. Conclusions
2. Buildings description, OCC, (IBC code)

The Onassis Foundation commissioned a group of engineering firms among which, the French architectural firm, Architecture Studio, and structural engineering firm Omete SA, to design the Onassis Cultural Center in Athens.
2. Buildings description, OCC, (IBC code)
Upper part of the basement

FPS type isolators are placed
2. Buildings description, OCC, (IBC code)
2. Buildings description, OCC, (IBC code)
Superstructure is considered elastically supported on the isolators in the vertical direction. Spring values are calculated after the analysis of the basement.

In the horizontal direction equivalent elastic or nonlinear properties are considered depending on the type of the analysis.
The Stavros Niarchos Foundation Cultural Center (SNFCC) is currently under construction in Athens and, when completed in 2016, will house the National Opera and Library of Greece.
The SNF commissioned architect Renzo Piano and a team of structural engineering firms (Expedition Engineering-Omete SA) to design the various structures of the complex.
The main structural challenges of the project are:

- very poor soil conditions
- high seismic performance expectations
- a demanding architectural concept
2. Buildings description, SNFCC, (EC-8)
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The Opera is the largest single building on the site. It is a RC structure, the dominant element of which is a cruciform shape formed by 5 adjacent cubes of the main and rear stage, side stages and the auditorium.

On top of the Opera lies the Canopy, a ferrocement structure supported on 30 steel columns.
2. Buildings description, SNFCC, (EC-8)

Library

The Library is a RC framed building, comprising of concrete columns, flat slabs and shear walls. It is a 3-storey structure with predominantly open-plan floor space and a sloping, fully landscaped roof. Storey heights are generally 6m with local mezzanine levels.
2. Buildings description, SNFCC, (EC-8)

Opera

For the superstructure and the basement/foundation two separate models are created in order to increase the accuracy and the ease of calculations.

Modeling is achieved through the use of FEM. Program code ETABS is used.
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Modeling is achieved through the use of FEM. Program code ETABS is used.
2. Buildings description, SNFCC, (EC-8)

Isolator & Seismic joint
3. Seismic design requirements

For both projects structural design had to meet very demanding architectural requirements as well as high performance seismic specifications. The latter impose design for higher seismic action than the one outlined by the code in force at the time of the design and operational performance level (no damages) after the design earthquake.
3. Seismic design requirements, OCC, (IBC)

Onassis Cultural Center

\[ \alpha = 0.24 \]
\[ \gamma_I = 1.15 \]
\[ q = 1.5 \]

Typical Building in Athens

\[ \alpha = 0.16 \]
\[ \gamma_I = 1.0 \]
\[ q = 3.5 \]

= 4 \times

more than 4 times greater demand
(in terms of spectral acceleration)
3. Seismic design requirements, SNFCC, (EC-8)

SNFCC Opera & Library

\[ \alpha = 0.27 \]
\[ \gamma_I = 1.4 \]
\[ q = 1.5 \]
\[ SA \text{ amp} = 3.0 \]

Typical Building in Athens

\[ \alpha = 0.16 \]
\[ \gamma_I = 1.0 \]
\[ q = 3.5 \]
\[ SA \text{ amp} = 2.5 \]

more than 5 times greater demand
(in terms of spectral acceleration)
3. Seismic design requirements

The architectural concept could not be met due to the high-performance seismic specifications so it was decided to incorporate a seismic isolation system in order to:

a. liberate the architectural concept from the limitations of seismic design
b. achieve operational performance level (no damages) under the design earthquake
c. protect the contents of the buildings and continue its function after an earthquake
d. reduce foundation loads
Three seismic isolation systems were considered:

a. Elastomeric bearings.
b. Steel spring bearings.
c. Friction-Pendulum bearings.

For the latter:
- the structure’s period is independent of the vertical load
- they provide adequate damping
- they provide the greatest durability and longevity
3. Selection of seismic isolation system

So from the 3 possible seismic isolation systems examined, FPS (SIP) bearings were selected.
4. Analyses

a. preliminary calculations using equivalent SDOF system
b. dynamic response spectrum analyses on 3D models
c. nonlinear time-history analyses on 3D models
4a. Calculations using equivalent SDOF system Modeling

The structure can be modeled as a single degree of freedom system having a mass, $m$, resting on an isolator of FPS type. Basic characteristics of the isolator are the radius of curvature, $R$, of the sliding surface and friction coefficient, $\mu$. $N_{sd}$ is the vertical load and $D$ is the horizontal displacement of the system.
4a. Calculations using equivalent SDOF system

Modeling

\[ K_{\text{eff}} = \frac{N_{sd}}{R} + \frac{\mu N_{sd}}{D} \]  

(1)

\[ N_{sd} = mg \]  

(2)

\[ T_{\text{eff}} = 2\pi \sqrt{\frac{m}{K_{\text{eff}}}} \]  

(3)

\[ T_{\text{eff}} = 2\pi \sqrt{\frac{RD}{gD + \mu gR}} \]  

(4)
4b. Dynamic RS analysis on 3D models

Dynamic Response Spectrum analysis on 3D models aim to:

a. Verify the fundamental period.
b. Calculate maximum displacements.
c. Check for uplift.
d. Design the structural system.
4c. Nonlinear time-history analyses on 3D models

Motions

In order to verify the design, a series of nonlinear time-history analyses are performed on the 3D models of the buildings. According to IBC and EC-8, three earthquake motions are selected, scaled and imposed to the structures.
4c. Nonlinear time-history analyses on 3D models

Records OCC

Based on soil properties (stiff soil) the selected earthquake records are: El Centro (Imperial Valley EQ, May 18, 1940, station #117), Kern (Kern County, California EQ, July 21, 1952, station #095) and Lower California (L. California EQ, December 30, 1934, station # 117).
4c. Nonlinear time-history analyses on 3D models

Records OCC

**Graph:**
- **SA (g)** vs **T (s)**
- **EL CENTRO EQ**
- **AVERAGE OF HOR. COMPONENTS**
- **DESIGN SPECTRUM**
  - $\alpha = 0.36, q = 1.0, n = 1.0$ (β = 5%)
### 4c. Nonlinear time-history analyses on 3D models

Records OCC

Scaling factors (SF) used, $T_R = 475 / 2400$ years

<table>
<thead>
<tr>
<th>Accelerogram</th>
<th>El Centro</th>
<th>Kern</th>
<th>Lower California</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF horizontal component</td>
<td>1.10 / 1.35</td>
<td>2.30 / 3.10</td>
<td>3.00 / 4.10</td>
</tr>
<tr>
<td>SF vertical component</td>
<td>1.05 / 1.15</td>
<td>2.10 / 2.60</td>
<td>2.70 / 3.70</td>
</tr>
</tbody>
</table>
4c. Nonlinear time-history analyses on 3D models

Records OCC

![Graph showing response spectra for different locations: Lower California, Kern EQ, El Centro EQ, and an average of horizontal components. The graph plots SA (g) against T (s).](image-url)
4c. Nonlinear time-history analyses on 3D models

Records SNFCC

The earthquake records are selected considering soil properties (soft soil), fault distance and magnitude of event. The selected records are:

- Gilroy # 1  (1989, M6.9 Loma Prieta EQ)
- Pacoima Dam  (1971 San Fernando EQ)
- Lefkada  (Lefkada, Greece Aug 14, 2003)

The motions are amplitude–and–frequency manipulated to be compatible with the elastic design response spectrum ($\xi=5\%$).
4c. Nonlinear time-history analyses on 3D models

Acceleration response spectra of the records used
4c. Nonlinear time-history analyses on 3D models
Scaling

For scaling

IBC: periods from $0.5T_{eff}$ to $1.25T_{eff}$
EC8: periods from $0.2T_{eff}$ to $2T_{eff}$

Conclusion: EC8 too conservative
### 5. IBC vs EC8

#### Design spectra parameters

OCC: For the design the IBC (NEHRP, SEAOC) code provisions are considered. Following the principles of capacity design these are the seismic parameters used:

<table>
<thead>
<tr>
<th></th>
<th>$T_R$</th>
<th>$\alpha$</th>
<th>$Y_1$</th>
<th>$q$</th>
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<tbody>
<tr>
<td>Superstructure</td>
<td>475 (DBE)</td>
<td>0.24</td>
<td>1.15</td>
<td>1.50</td>
</tr>
<tr>
<td>Substructure</td>
<td>475 (DBE)</td>
<td>0.24</td>
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<td>1.00</td>
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<td>Isolation system</td>
<td>2400 (MCE)</td>
<td>0.36</td>
<td>1.00</td>
<td>1.00</td>
</tr>
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</table>
5. IBC vs EC8

Design spectra parameters

OCC: Superstructure and basement are analysed for the design basis earthquake DBE ($T_R=475$ years) but using different behavior factors.

Isolation system is analysed for the maximum considered earthquake MCE ($T_R=2400$ years).

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5. IBC vs EC8
Design spectra parameters

Design Spectra OCC
SNFCC: For the design the EC8 code provisions are considered. Following the principles of capacity design, superstructures and undercrofts are analysed for the design earthquake but using different behavior factors. For the isolation system the displacement is checked using a magnification factor of $y_x = 1.5$

<table>
<thead>
<tr>
<th></th>
<th>$\alpha$</th>
<th>$\gamma$</th>
<th>$q$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superstructure</td>
<td>0.27</td>
<td>1.4</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Undercroft</td>
<td>0.27</td>
<td>1.4</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Isolation system (only displacement)</td>
<td>0.40</td>
<td>1.4</td>
<td>1.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>
5. **IBC vs EC8**

Design spectra parameters
5. IBC vs EC8

Design spectra parameters

Instead of using the concept of MCE, EC8 implements a magnification factor of $\gamma_x = 1.2 - 1.5$

Conclusion: EC8 too conservative
5. IBC vs EC8
Vertical Spectra

IBC: suggestion to use 20% of the horizontal spectrum values.
In practice for seismic isolation, values of 2/3 of the horizontal may be used as a conservative approach.

EC8: vertical spectra $a_{vg}/a_g = 0.9$ (but soil factor $S = 1$ in all cases).
This results to values between 65% - 90% of the horizontal.

Conclusion: EC8 too conservative.
5. IBC vs EC8
friction coefficient $\mu$

For the friction coefficient, $\mu$, a mean value is selected.

According to IBC and EN 15129, two sets of design properties of the system of devices shall be properly established:
(a) Upper bound design properties (UBDP)
(b) Lower bound design properties (LBDP)

So in order to check the isolation system using t-h analyses, two structural models should be examined: one for which the higher value of friction coefficient is used (UBDP), critical for reactions and another for which the lower value of friction coefficient is used (LBDP) and is critical for displacements.
5. IBC vs EC8
friction coefficient $\mu$

IBC: $\mu$ in the range of $\pm 15\%$

EC8: $\mu$ in the range of $\pm 30\%$

Conclusion: EC8 too conservative
6. Conclusions

(1) The suggested methodologies from both codes are similar

(2) EC8 is more conservative in:
   a. Use of Magnification factor instead of MCE
   b. Vertical Spectrum
   c. Range of properties of isolators
   d. Scaling of accelerograms
References

For parts of this presentation, information from the following papers has been used:
