Masonry out-of-plane analysis

Advanced Earthquake Engineering
CIVIL-706

Instructor:
Lorenzo DIANA, PhD
Content

• Analysis of local collapse mechanisms in masonry buildings
• Kinematic approach
• Linear verification
• Non-linear verification
• Detection of possible mechanisms
• NTC – LV1 church-form assessment
• The Sion Cathedral
Content

• Analysis of local collapse mechanisms in masonry buildings
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Analysis of local collapse mechanism in masonry buildings

- Masonry buildings are subject to partial collapses during earthquake due to loss of equilibrium of masonry portions.
- Analysis of local mechanisms is one of the main issues in the seismic analysis of masonry buildings.
- Out-of-plane mechanisms are the most important ones.
- Different causes of local mechanisms: low masonry quality, difficulties in maintenance (ex. heritage masonry buildings show worse behaviour than standard ones).
Analysis of local collapse mechanism in masonry buildings

Main local out-of-plane mechanisms

• Simple Overturning
• Vertical Bending
• Horizontal Bending
• Composite Overturning
• Overturning of the top of facade
• Overturning of the corner
• ...

Masonry out-of-plane analysis
Analysis of local collapse mechanism in masonry buildings

Simple Overturning
Analysis of local collapse mechanism in masonry buildings

Simple Overturning

- Overturning of the whole facade (or part of the facade)
- Overturning of a two part masonry wall
Analysis of local collapse mechanism in masonry buildings

Vertical Bending
Analysis of local collapse mechanism in masonry buildings

**Vertical Bending**

- Simple vertical bending (one storey wall or multiple storey wall)

- Vertical bending of a two part masonry wall
Analysis of local collapse mechanism in masonry buildings

Horizontal Bending
Analysis of local collapse mechanism in masonry buildings

Horizontal Bending

- Simple horizontal bending
- Simple horizontal bending of a two part masonry wall
Analysis of local collapse mechanism in masonry buildings

Composite Overturning
Analysis of local collapse mechanism in masonry buildings

Composite Overturning

- Composite overturning with diagonal shaped wedges

- Composite overturning with double diagonal shaped wedges
Analysis of local collapse mechanism in masonry buildings

Composite Overturning
Analysis of local collapse mechanism in masonry buildings

Overturning of the top of facade
Analysis of local collapse mechanism in masonry buildings

Overturning of the corner
Analysis of local collapse mechanism in masonry buildings

Causes

- Poor masonry quality:
  - No box behaviour
  - Poor corner brick teething (no connection between 90° walls)
  - No transversal connection between different parts of the wall
  - No connection between slabs and walls (flexible slabs)
- Main problems are detected in churches and monuments
- Continuous modification of historical buildings
- Large dimensions and poor maintenance
- Relationship between restoration / maintenance / strengthening
Analysis of local collapse mechanism in masonry buildings

No box behaviour

Foto: Diana (Amatrice 2016)
Analysis of local collapse mechanism in masonry buildings

Poor corner brick teething

Analysis of local collapse mechanism in masonry buildings

No transversal connection between different parts of the walls

Foto: Diana (Amatrice 2016)
Analysis of local collapse mechanism in masonry buildings

No transversal connection between different parts of the walls

Foto: Podestà, Diana
Analysis of local collapse mechanism in masonry buildings

Roof elements not connected to the walls

Analysis of local collapse mechanism in masonry buildings

No connection between structural elements and non structural walls

Foto: Diana (Amatrice 2016)
Analysis of local collapse mechanism in masonry buildings

Causes

• Poor masonry quality:
  – No box behaviour
  – Poor corner brick teething (no connection between 90° walls)
  – No transversal connection between different parts of the wall
  – No connection between slabs and walls (flexible slabs)

• Main problems are detected in churches and monuments

• Continuous modification of historical buildings

• Large dimensions and poor maintenance

• Relationship between restoration / maintenance / strengthening
Analysis of local collapse mechanism in masonry buildings

Continuous modification of historical buildings

Chiesa Santa Maria degli Angeli (Roma)
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• Detection of possible mechanisms

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• The Sion Cathedral
Kinematic approach

Approach of Italian Building Code NTC2008

1) Transformation of the macroelement into a unstable system
2) Determination of the horizontal multiplier $\alpha_0$ activating the mechanism
3) Evaluation of the evolution of $\alpha$ with increase in displacement $d_k$ of a control point
4) Transformation of the capacity curve into a spectral curve
5) Verification
Kinematic approach

Approach of Italian Norm NTC2008

Conditions:
- Rigid body
- No breaking up of masonry
- No tensile strength
- No sliding between bricks
Kinematic approach

Simple Overturning – definition of load multiplier $\alpha_0$

Determination of load multiplier $\alpha_0$

1) P. V. W.

$$W_{\text{ext}} - W_{\text{int}} = 0 \text{ (no } W_{\text{int}})$$

$$\alpha_0 \left( \sum_{i=1}^{n} P_i \cdot \delta_{x,i} + \sum_{j=n+1}^{n+m} P_j \cdot \delta_{x,j} \right) + \sum_{h=1}^{o} F_h \cdot \delta_h - \sum_{i=1}^{n} P_i \cdot \delta_{y,i} = W_{\text{int}}$$

$$\alpha_0 \cdot P \cdot u_G - P \cdot v_G = 0$$

$$u_G = -\theta \cdot \frac{H}{2}; v_G = -\theta \cdot \frac{B}{2};$$

$$\rightarrow -\alpha_0 P \cdot \theta \cdot \frac{H}{2} - P \cdot (-\theta) \cdot \frac{B}{2} = 0$$

$$\rightarrow \alpha_0 = \frac{B}{H}$$
Simple Overturning – definition of load multiplier $\alpha_0$

Determination of load multiplier $\alpha_0$

1) Equilibrium to rotation (C)

Overturning moment

$-\alpha_0 \cdot P \cdot H/2$

Stabilizing moment

$P \cdot B/2$

Equilibrium

$\alpha_0 \cdot P \cdot H/2 = P \cdot B/2$

$\alpha_0 = B/H$
Kinematic approach

Simple Overturning – capacity curve $\alpha - d_k$

- Evaluation of the load multiplier $\alpha$ not only in the initial configuration ($\alpha_0$) but also during the evolution of the mechanism.
- $d_k$ is the displacement of a defined control point, usually chosen at the centre of application of all forces.
Kinematic approach

Simple Overturning – equivalent SDOF system

\[ a^* = a_0^* \left( 1 - \frac{d^*}{d_0^*} \right) \]

Transformation of the capacity curve into spectral curve.
Kinematic approach

Simple Overturning – equivalent SDOF system

Introduction of participating mass $M^*$:

$$M^* = \frac{(\sum_{i=1}^{n+m} P_i \delta_{x,i})^2}{g \sum_{i=1}^{n+m} P_i \delta_{x,i}}$$

Introduction of mass participation factor $e^*$:

$$e^* = \frac{gM^*}{\sum_{i=1}^{n+m} P_i}$$
Kinematic approach

Simple Overturning – equivalent SDOF system

Determination of the spectral acceleration that activates the mechanism:

\[ a_0^* = \frac{\alpha_0 \sum_{i=1}^{n+m} P_i}{M^* FC} = \frac{\alpha_0 g}{e^* FC} \]
Kinematic approach

Simple Overturning – equivalent SDOF system

Determination of the spectral displacement:

\[ d^* = d_k \frac{\sum_{i=1}^{n+m} P_i \delta_{x,i}^2}{\delta_{x,k} \sum_{i=1}^{n+m} P_i \delta_{x,i}} \]

Capacity Curve \( a^* - d^* \) (rigid body)
Kinematic approach

Simple Overturning – equivalent SDOF system

\[ a^* = a_0^* \left(1 - \frac{d^*}{d_0^*}\right) \quad \text{if } a^* > d_y^* \]

Capacity Curve \( a^*-d^* \) (bilinear)

When no specific evaluation of the period \( T \) is possible, a reference value \( T=0.1 \)s may be assumed. The spectral yielding displacement is given by:

\[ d_y^* = a_0^* T^2 \left(4\pi^2 + \frac{a_0^* T^2}{d_0^*}\right)^{-1} \]
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Linear verification

The safety of the structure against the considered collapse mechanism is satisfied if:

\[ a_0^* \geq a_g(\text{limit state}) \]

**SLD: damage limit state**

\[ a_g(\text{SLD}) = a_g(P_{VR}) \cdot S \]

- \( S \) is the soil multiplier
- \( P_{VR} \) probability of observing a seismic action of return period \( T_R \) during a reference time \( V_R \)

**SLV: life limit state**

\[ a_g(\text{SLV}) = \frac{a_g(P_{VR}) \cdot S}{q} \]

- \( q \) is a hypothetic strength reduction factor assumed to be 2
Linear verification

The safety of the structure against the considered collapse mechanism is satisfied if:

\[ a_0^* \geq a_g(\text{limit state}) \]

In case the mechanism involves a portion of the structure at a given height from the ground, \( a_g(SLD) \) can be calculated as:

\[
a_g(SLD) = S_{ae}(T_1) \cdot \Psi(Z) \cdot \gamma
\]

- \( S_{ae}(T_1) \) is the acceleration for period \( T_1 \) from the elastic acceleration spectrum;
- \( T_1 \) is the first period of the structure;
- \( \Psi(Z) \) is the first vibration mode in the considered direction, normalized to 1 on top of the structure; it can be calculated as \( \Psi(Z) = Z/H \), where \( H \) is the whole height of the structure and \( Z \) is the height of the structure from the base to constraint of the mechanism;
- \( \gamma \) is the corresponding coefficient of modal participation, calculated as \( \gamma = 3N/(2N + 1) \), with \( N \) the number of floors of the building;
The safety of the structure against the considered collapse mechanism is satisfied if:

\[ a_0^* \geq a_g(\text{limit state}) \]

In case the mechanism involve a portion of the structure at a given height from the ground, \( a_g(SLV) \) can be calculated as:

\[ a_g(SLV) = \left( S_{ae}(T_1) \cdot \Psi(Z) \cdot \gamma \right) / q \]

- \( S_{ae}(T_1) \) is the acceleration for period \( T_1 \) from the elastic spectrum of acceleration;
- \( T_1 \) is the first period of the structure;
- \( \Psi(Z) \) is the first vibration mode in the considered direction, normalized to 1 on top of the structure; it can be calculated as \( \Psi(Z) = Z/H \), where \( H \) is the whole height of the structure and \( Z \) is the height of the structure from the base to constraint of the mechanism;
- \( \gamma \) is the corresponding coefficient of modal participation, calculated as \( \gamma = 3N/(2N + 1) \), with \( N \) the number of floors of the building;
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Non-Linear verification

In the non-linear field, the verification is performed between the ultimate displacement $d_u^*$ of the local mechanism analysed and the displacement demand $\Delta_d(T_S)$ obtained by the response spectrum at a certain $T_S$.

$$d_u^* \geq \Delta_d(T_S)$$

$d_u^*$ is calculated as the lower value between:

$$d_u^* = 0.4 \cdot d_0^*$$ (Doherty et al. 2000/2002; Griffith et al. 2003)

and

$$d_u^* = d$$ that causes local instability (ex. Slipping out of wood beam)
Non Linear verification

In the non-linear field, the verification is performed between the ultimate displacement $d_u^*$ of the local mechanism analysed and the displacement demand $\Delta_d(T_S)$ obtained by the response spectrum at a certain $T_S$.

$$d_u^* \geq \Delta_d(T_S)$$

$\Delta_d(T_S)$ is the performance point, defined as:

$$\Delta_d(T_S) = S_{de}(T_S)$$

Where,

$S_{de}(T_S)$ is the elastic displacement demand at a certain $T_S$.

How is $T_S$ defined?
Non Linear verification

Definition of $T_S$?
A statistical analysis (Lagomarsino 2005) on the results of non-linear dynamic analyses with different earthquakes shows that $T_S$ was given by the interpolation of:
- the period obtained in correspondence of a displacement equal to $0.5d_u^*$
- the elastic period
Non Linear verification

The Italian Building Code proposes:

\[ d_s^* = 0.4 \cdot d_u^* \]

\[ T_s = 2\pi \sqrt{\frac{d_s^*}{a_s^*}} \]

\[ a_s^* = a_0^* \left( 1 - \frac{d_s^*}{d_0^*} \right) \]
Non Linear verification

Verification

\[ d_u^* \geq \Delta_d(T_S) \]

\[ \Delta_d(T_S) = S_{de}(T_S) \]

In case the mechanism involves a portion of the structure at a given height from the ground, \( \Delta_d(T_S) \) can be calculated as:

\[ \Delta_d(T_S) = S_{de}(T_1) \cdot \Psi(Z) \cdot \gamma \cdot \sqrt{\left(1 - \frac{T_S}{T_1}\right)^2 + 0.02 \cdot \frac{T_S}{T_1}} \]

Where,

\[ T_1 = 0.05 \cdot H^{0.75} \]
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Detection of possible mechanisms

Overturning of the apse; Apse vaults

Santuario delle Madonna Icona Passatora – Ferrazza (Amatrice)
Detection of possible mechanisms

Overturning of the apse

Santuario delle Madonna Icona Passatora – Ferrazza (Amatrice)
Detection of possible mechanisms

Collapse of the top of the main facade
Detection of possible mechanisms

Belfry

Chiesa S. Alfonso dei Liguori – Colletorto (CB)
Detection of possible mechanisms

Collapse of the top of the main façade; cross response of the church
Detection of possible mechanisms

Collapse of the top of the main façade; cross response of the church
Detection of possible mechanisms

In plane mechanism of the facade

Triumphal arch

Projections

Cross response of the church

Chiesa SS. Marciano e Nicandro a L’Aquila (sisma 2009)
**Detection of possible mechanisms**

**Overturning of the main facade**

<table>
<thead>
<tr>
<th>Linear Verification</th>
<th></th>
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<tbody>
<tr>
<td>SLD</td>
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<td>$a_{\text{SLD}} \text{[m/s}^2\text{]}$</td>
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<tr>
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**Non-Linear Verification**

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**Mechanism of the triumphal arch**

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<tbody>
<tr>
<td>SLD</td>
<td>$a_0^* \text{[m/s}^2\text{]}$</td>
<td>$a_{\text{SLD}} \text{[m/s}^2\text{]}$</td>
<td>Verification</td>
</tr>
<tr>
<td></td>
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<tr>
<td>SLV</td>
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<tr>
<td></td>
<td>1.379</td>
<td>1.249</td>
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**Non-Linear Verification**

<table>
<thead>
<tr>
<th>SLV</th>
<th>$d_u^* \text{[m]}$</th>
<th>$\Delta_d(T_s) \text{[m]}$</th>
<th>Verification</th>
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<tbody>
<tr>
<td></td>
<td>0.148</td>
<td>0.041</td>
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Chiesa SS. Marciano e Nicandro a L'Aquila (sisma 2009)
Detection of possible mechanisms

Overturning of the top of the apse

<table>
<thead>
<tr>
<th>Linear Verification</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SLD</strong></td>
<td><em><em>a₀</em> [m/s²]</em>*</td>
<td><strong>a_{SLD} [m/s²]</strong></td>
<td><strong>Verification</strong></td>
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<tr>
<td><em><em>a₀</em> ≥ a_{g(P_{fr})} S</em>*</td>
<td>1.260</td>
<td>1.248</td>
<td>Yes</td>
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<tr>
<td><em><em>a₀</em> ≥ S_{d}(T_{1}) \cdot \Psi(2) \cdot \gamma</em>*</td>
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<tr>
<td><strong>SLV</strong></td>
<td><em><em>a₀</em> [m/s²]</em>*</td>
<td><strong>a_{SLV} [m/s²]</strong></td>
<td><strong>Verification</strong></td>
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<tr>
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<td>1.260</td>
<td>1.499</td>
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<td><em><em>a₀</em> ≥ S_{d}(T_{1}) \cdot \Psi(2) \cdot \gamma</em>*</td>
<td>1.260</td>
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<table>
<thead>
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<td><strong>SLV</strong></td>
<td><em><em>d_u</em> [m]</em>*</td>
<td><strong>\Delta_{d}(T_{1}) [m]</strong></td>
<td><strong>Verification</strong></td>
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<tr>
<td><em><em>d_u</em> ≥ S_{de}(T_{3})</em>*</td>
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<tr>
<td><em><em>d_u</em> ≥ S_{de}(T_{1}) \cdot \Psi(2) \cdot \gamma \cdot \ldots</em>*</td>
<td>0.022</td>
<td>0.080</td>
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</table>
Detection of possible mechanisms

Cross response of the church

### Linear Verification

<table>
<thead>
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<th>$a_0^*$ [m/s²]</th>
<th>$a_{SLD}$ [m/s²]</th>
<th>Verification</th>
</tr>
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<td>$a_0^* \geq a_d(P_{mR})$</td>
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### Non-Linear Verification

<table>
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<tr>
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<th>$d_u^*$ [m]</th>
<th>$\Delta_d(T_s)$ [m]</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLD</td>
<td>0.173</td>
<td>0.120</td>
<td>Yes</td>
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<tr>
<td>$d_u^* \geq S_{dR}(T_s)$</td>
<td>0.173</td>
<td>0.064</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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• **NTC – LV1 church-form assessment**
• The Sion cathedral
**NTC – LV1 church form assessment**

**Linee Guida per la Valutazione e Riduzione del Rischio Sismico del Patrimonio Culturale**

**Rilievo della Vulnerabilità Sismica delle Chiese**

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### MODULO D – ANALISI DEL DANNO E DELLA VULNERABILITÀ

#### 1 – Ribalmento della Facciata

| Presenza del macroelemento in relazione al meccanismo: Si ☑ No ☑ |
|---|---|
| **Vulnerabilità** | **Presidi antissimici** | **Indicatori di vulnerabilità** | **Danno** |
| Si ☑ | ☑ Presenza di catene longitudinali | ☑ Presenza di elementi puniti di copertura | ☑ Distacco della facciata dalle pareti o evidenti fuori piombo |
| No ☑ | ☑ Presenza di effetti elementi di contrasto (contrafforti, corpi addossati, altri edifici) | ☑ Presenza di elementi pungenti (puntini di copertura, volte, archi) | ☑ |
| | ☑ Ammoramenti di buona qualità tra la facciata ed i muri della navata | ☑ Presenza di grandi aperture nelle pareti laterali in vicinanza del cantiere | ☑ |

#### 2 – Meccanismi nella Sommità della Facciata

| Presenza del macroelemento in relazione al meccanismo: Si ☑ No ☑ |
|---|---|
| **Vulnerabilità** | **Presidi antissimici** | **Indicatori di vulnerabilità** | **Danno** |
| Si ☑ | ☑ Presenza di collegamenti puntuali con la copertura (travi-catene) | ☑ Presenza di controventi di falda | ☑ Lesioni inclinate a (taglio) – Lesioni verticali o arcuate – Rotazioni delle capriate |
| No ☑ | ☑ Presenza di cordoli leggeri (metallici reticolari, muratura armata, c.a. ottovi) | ☑ Presenza di grandi aperture (rosone o altro) | ☑ |
| | | ☑ Presenza di una sommità a veia di grande dimensione e peso | ☑ |
| | | ☑ Cordoli rigidì, trave di colmo in c.a., copertura pesante in c.a. | ☑ |

#### 3 – Meccanismi nel Piano della Facciata

| Presenza del macroelemento in relazione al meccanismo: Si ☑ No ☑ |
|---|---|
| **Vulnerabilità** | **Presidi antissimici** | **Indicatori di vulnerabilità** | **Danno** |
| Si ☑ | ☑ Presenza di catene in controfacciata | ☑ Presenza di grandi aperture (anche tamponeate) | ☑ Lesioni inclinate (taglio) – Lesioni verticali o arcuate (rotazione) – Altre fessurazioni o spianamenti |
| No ☑ | ☑ Contrasto laterale fornito da corpi addossati o facciata inserita in aggregato | ☑ Elevata snellezza (rapporto altezza/larghezza) | ☑ |

#### 4 – Protiro - Narcente

| Presenza del macroelemento in relazione al meccanismo: Si ☑ No ☑ |
|---|---|
| **Presidi antissimici** | ☑ Peso nella fabbrica (≤1): ___ |
NTC – LV1 church form assessment

- LV1-church form is a simplified survey-form.
- LV1-church form provides a qualitative method to assess the general vulnerability of masonry churches.
- The Italian Building Code provides different survey-forms for different typology of masonry constructions.
- LV1-church survey-form, through a series of evaluation on each possible collapse mechanism, leads to the assessment of a global vulnerability index.
- 28 mechanisms are evaluated (in-plane and out-of-plane).
**NTC – LV1 church form assessment**

### POSSIBLE COLLAPSE MECHANISMS

<table>
<thead>
<tr>
<th>01. Overturning of the facade</th>
<th>02. Collapse of the top of the facade</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>03. In-plan mechanism of the facade</th>
<th>04. Narthex</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
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</table>

<table>
<thead>
<tr>
<th>05. Cross response of the church</th>
<th>06. In-plan shear mechanism of side facades</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
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</table>

<table>
<thead>
<tr>
<th>07. Lengthwise response of the colonnade</th>
<th>08. Nave vaults</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>09. Aisles vaults</th>
<th>10. Overturning of transept walls</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
</tr>
</tbody>
</table>

### 11. In-plan shear mechanism of transept walls

- ![Diagram](image11)

### 12. Transept vaults

- ![Diagram](image12)

### 13. Triornphal arches

- ![Diagram](image13)

### 14. Dome - tambour

- ![Diagram](image14)

### 15. Lantern

- ![Diagram](image15)

### 16. Apse overturning

- ![Diagram](image16)

### 17. In-plan shear mechanism in apse

- ![Diagram](image17)

### 18. Apsis vaults

- ![Diagram](image18)
The Italian norm, by the application of a simplified survey-form based on mechanical models, provides a qualitative method to assess the general vulnerability of masonry churches. In these guidelines, different survey-forms are provided for different typology of masonry construction: standard palaces and villas; churches; towers; arches and bridges.
The vulnerability index is described by the following expression:

\[ i_v = \frac{\sum_{k=1}^{28} \rho_k (v_{ki} - v_{kp})}{6} + \frac{1}{2} \]

- where:
  - \( i_v \) is the vulnerability index;
  - \( k \) are the twenty-eight possible collapse mechanisms;
  - \( \rho_k \) is the importance weight of the mechanism (between 0.5 and 1.0; equal to 0 if the mechanism is absent);
  - \( v_{ki} \) is the generic score evaluated for the examined mechanism in terms of vulnerability;
  - \( v_{kp} \) is the generic score evaluated for the examined mechanism in terms of protection devices;
The evaluation of the $v_{ki}$ and $v_{kp}$ score starts with filling of the survey-form and by application of the standardization process.
NTC – LV1 church form assessment

The Italian Building Code defines a preliminary value for the capacity seismic limit for $a^*_{g\,(SLD)}$ and $a^*_{g\,(SLV)}$, related to the vulnerability index $i_v$.

The capacity seismic limit $a^*_{g\,(SLD)}$ is described as follows:

$$a^*_{g\,(SLD)} = 0.025 \cdot 1.8^{2.75-3.44i_v}$$

The capacity seismic limit $a^*_{g\,(SLV)}$ is described as follows:

$$a^*_{g\,(SLV)} = 0.025 \cdot 1.8^{5.1-3.44i_v}$$
Content

• Analysis of local collapse mechanisms in masonry buildings
• Kinematic approach
• Linear verification
• Non-linear verification
• Detection of possible mechanisms
• NTC – LV1 church-form assessment
• The Sion Cathedral
Sion Cathedral

Overlapping of history layers

Clocher-porche

1947

XI sec.

XII-XIII sec.

XV-XVI sec.
The Sion Cathedral

Internal view of the nave covered by cross vaults

South façade of the Cathedral of Sion
The Sion Cathedral

Corner brick teething
The Sion Cathedral

Buttresses

Tie rods in the transept walls
The Sion Cathedral

LV1-church survey-form – vulnerability index

• The application of the LV1-church form on the Sion Cathedral provides the global index of vulnerability ($i_v$) of the building and meanwhile a simplified value of the general response. The vulnerability index is given by the assessment of the vulnerability connected to the 28 different possible collapse mechanisms.
## LV1 church survey-form – vulnerability index

<table>
<thead>
<tr>
<th>Mechanism number</th>
<th>Mechanism name</th>
<th>$V_{ki}$</th>
<th>$V_{kp}$</th>
<th>$\rho_k$</th>
<th>$i_{vk}$</th>
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<tbody>
<tr>
<td>1</td>
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<td>3</td>
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<tr>
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<td>2</td>
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<td>-1</td>
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<tr>
<td>7</td>
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<td>3</td>
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<tr>
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<tr>
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<td>Triumphal arches</td>
<td>0</td>
<td>3</td>
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<td>-3</td>
</tr>
<tr>
<td>14</td>
<td>Dome - tambour</td>
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<td>-</td>
<td>0</td>
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<td>Lantern</td>
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<td>Interaction with irregular elements</td>
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<td>Projections</td>
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<td>Bell tower</td>
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<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>28</td>
<td>Belfry</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
The Sion Cathedral

LV1 church survey-form – vulnerability index

\[ i_V = \frac{1}{6} \sum_{k=1}^{28} \rho_k (v_{ki} - v_{kp}) + \frac{1}{2} \]

<table>
<thead>
<tr>
<th>( i_V )</th>
<th>Seismic limit ( a^*_g(SLV) ) [m/s²]</th>
<th>Seismic demand ( a_g(SLV) ) [m/s²]</th>
<th>( \alpha_{eff} ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>1.991</td>
<td>1.296</td>
<td>1.54</td>
</tr>
</tbody>
</table>
The Sion Cathedral

LV1 church survey-form – mechanisms detection

By the analysis of the 28 mechanisms, it’s possible to take into account the following:

- the dangerous mechanisms are those with high value related to the global vulnerability aspects ($v_{ki}$) and the absence or the lack of protection devices; it is possible to identify:
  - the mechanism related to the apse roof elements (N. 21) has a global vulnerability index ($i_{vk} = 2$) equal to 2;
  - the mechanism of the belfry (N. 28) has a global vulnerability index ($i_{vk} = 2$) equal to 2;
  - the mechanism of overturning of chapels (N. 22) has a vulnerability index ($i_{vk} = 1$) equal to 1;

- Other important mechanisms are those with and high value related to the vulnerability aspects ($v_{ki} = 3$); this because of the uncertainty to evaluate the capacity of same protection devices (especially the metal chains); it is possible to identify:
  - the overturning of the south facade (N. 1) has the value related to the vulnerability aspects ($v_{ki} = 3$) equal to 3;
  - the apse overturning (N. 16) has the value related to the vulnerability aspects ($v_{ki} = 3$) equal to 3;
  - the in-plan shear mechanism in apse (N. 17) has the value related to the vulnerability aspects ($v_{ki} = 3$) equal to 3;
  - the mechanism related to the bell tower (N. 27) has the value related to the vulnerability aspects ($v_{ki} = 3$) equal to 3.
The Sion Cathedral

Mechanisms analysed

• Overturning of Saint-Barbe chapel walls
• Overturning of the south facade of the building
• Overturning of the apse
• Central arch
The Sion Cathedral

Overturning of Saint-Barbe chapel walls

Illustration of the wall involved in the considered mechanism of Saint-Barbe chapel
The Sion Cathedral

Overturning of Saint-Barbe chapel walls

Elements involved in the collapse mechanism (UP)
Collapse mechanism scheme (RIGHT)
The Sion Cathedral

Overturning of Saint-Barbe chapel walls

Capacity curve

\[ \alpha \text{ [-]} \]

Control point at:
\[ h_{\text{bar}} = 4.13 \text{ m} \]
from hinge A

Capacity curve \((\alpha - d_k)\)
# The Sion Cathedral

## Overturning of Saint-Barbe chapel walls

<table>
<thead>
<tr>
<th>Geometry of macroelements</th>
<th>Loads on macroelements</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness $s_i$ [m]</td>
<td>distance of $T$ to $A$ [m]</td>
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<tr>
<td>1.00</td>
<td>0.83</td>
</tr>
<tr>
<td>Heigh of application of $PV_i$ [m]</td>
<td>distance of $PV_3$ to $A$ [m]</td>
</tr>
<tr>
<td>5.15</td>
<td>7.00</td>
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</table>

<table>
<thead>
<tr>
<th>Stabilizing moments</th>
<th>Overturning moments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self Weight $T_v$ [kNm]</td>
<td>Roof vert $\Sigma PV_{vi}$ [kNm]</td>
</tr>
<tr>
<td>2054.14</td>
<td>23.14</td>
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The Sion Cathedral

Overturning of Saint-Barbe chapel walls

<table>
<thead>
<tr>
<th>Horizontal load multiplier</th>
<th>Linear verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha_0)</td>
<td>(\text{Partecipant mass } M^*)</td>
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<tr>
<td>0.296</td>
<td>179.356</td>
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</table>

<table>
<thead>
<tr>
<th>Spectral capacity curve</th>
<th>Non-linear verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral displacement</td>
<td>Ultimate displacement</td>
</tr>
<tr>
<td>(d_{0}^*)</td>
<td>(d_u^*)</td>
</tr>
<tr>
<td>[m]</td>
<td>[m]</td>
</tr>
<tr>
<td>1.199</td>
<td>0.479</td>
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</table>
The Sion Cathedral

Overturning of Saint-Barbe chapel walls

Spectral capacity curve and ADSR spectrum
The Sion Cathedral

Overturning of the south facade of the building
The Sion Cathedral

Overturning of the apse

Mech. A

Mech. B
The Sion Cathedral

Central Arch

Mech. 1

Mech. 2

Mech. 3
The Sion Cathedral

Summary of safety coefficients obtained from analysis of local mechanisms

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Importance factor $\gamma_1 = 1.2$</th>
<th>Importance factor $\gamma_1 = 1.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha_{eff}$ [-]</td>
<td>$\alpha_{eff}$ [-]</td>
</tr>
<tr>
<td></td>
<td>Linear analysis</td>
<td>Non-linear analysis</td>
</tr>
<tr>
<td>Overturning Saint Barbe chapel</td>
<td>2.27</td>
<td>3.06</td>
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<tr>
<td>Overturning south facade</td>
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<td>1.52</td>
</tr>
<tr>
<td>Overturning of the apse (A)</td>
<td>0.98</td>
<td>1.81</td>
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<tr>
<td>Overturning of the apse (B)</td>
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<td>Central Arch (1)</td>
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<td>1.87</td>
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<td>Central Arch (2)</td>
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<td>Central Arch (3)</td>
<td>1.33</td>
<td>2.44</td>
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## LV1 church survey-form – vulnerability index

<table>
<thead>
<tr>
<th>Mechanism number</th>
<th>Mechanism name</th>
<th>$V_{ki}$</th>
<th>$V_{kp}$</th>
<th>$\rho_k$</th>
<th>$i_{vk}$</th>
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</thead>
<tbody>
<tr>
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<tr>
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<td>Collapse of the top of the facade</td>
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<td>-</td>
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<tr>
<td>3</td>
<td>In-plan mechanism of the facade</td>
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<tr>
<td>4</td>
<td>Narthex</td>
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<tr>
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<td>2</td>
<td>1</td>
<td>-1</td>
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<td>3</td>
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<td>7</td>
<td>Lengthwise response of the colonnade</td>
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<tr>
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<td>-3</td>
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<tr>
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<td>Dome - tambour</td>
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