Deliverable 3.1

Inventory of earthquake-induced failure mechanisms related to construction types, structural elements, and materials

ANNEX 1 – DAMAGE ABACUS

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WORKPACKAGE 3: Damage based selection of technologies

Leader: POLIMI

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### 1 DAMAGE DUE TO THE MASONRY CHARACTERISTICS

#### 1.1- IN PLANE MECHANISMS

**1.1.1 Damages due to horizontal actions**

Typical failure modes of masonry piers due to horizontal loads: (a) rocking; (b) sliding shear failure; and (c) diagonal cracking.

<table>
<thead>
<tr>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Sub-vertical cracks" /></td>
<td><img src="image" alt="Sliding on a horizontal plane" /></td>
<td><img src="image" alt="Diagonal crack" /></td>
</tr>
</tbody>
</table>

**1.1.2 Homogeneous / good masonry quality**

Cracks with characteristic angle between 30° and 45°.

(8)

**1.1.3 Mediocre masonry quality**

Cracks with characteristic angle between 15° and 30°.

(8)

**1.1.4 Weak / poor masonry quality**

Cracks with characteristic angle between 0° and 15°.

(8)
1.2 OUT OF PLANE MECHANISMS

1.2.1 Masonry section: poor or absence of connection between the leaves (see 2.2.2)

Leaves separation. Local overturning of the external leaf.

1.2.2 Masonry section: partial connection of the leaves (see 2.2.2)

Possible leaves separation. Possible local leaf overturning related to the restraint distribution and geometry.

1.2.3 Masonry section: good connection between the leaves (see 2.2.2)

Monolithic behaviour. Global overturning.
1.2.4 Masonry section with timber lacing: poor or absence of connection between the stone masonry leaves and decay of the timber lacing

a- Undamaged stage
Three-leaf masonry wall with double timber lacing at floor level.

b- Start of the collapse
Decay of inner timber lacing leads to overturning of the upper masonry assemblage and start of the collapse of the inner core constructed with rubble stone and poor or decayed mortar.
c- Collapse development
Progressive overturning leads to the destruction of the decayed outer timber lacing, further collapse of the inner core and separation of outer leaves.

1.2.5 Cladding separation caused by seismic action
Different configuration of cladding connections and possible failures

1.2.6 Overturning caused by seismic action (for adobe buildings)

1.2.7 Damage typology for rammed earth buildings
1.2.8 Damage typology for cob buildings

Vertical cracking, some cracking starts at base and stops at lifts, some runs through the height of the wall, which can result in overturning in single wall.

Vertical cracking at corner.
2 DAMAGE DUE TO THE ELEMENTS CHARACTERISTICS

2.1 IN-PLANE KINEMATICS MODEL FOR A WALL UNDER IN-PLANE ACTIONS (WALL SECTS SEPARATED BY WINDOWS)

2.1.1 Single wall

\[ \delta = \alpha \varphi \]

2.1.2 Multiple wall system

\[ \delta = \varphi_1 + \varphi_2 + \varphi_3 \]

2.2 KINEMATICS MODELS FOR OUT-OF-PLANE MECHANISMS - VERTICAL STRIPS

2.2.1 Overturning of a monolithic wall simply supported by the orthogonal wall
2.2.2 Overturning of a double-leaves wall simply supported by the perpendicular wall
(see from 1.2.1 to 1.2.3)

2.2.3 Global overturning of multi-storey walls not connected to the orthogonal walls

Overturning of vertical strip – Depending on the openings lay-out
2.2.4 Overturning with one or two side wings

Lateral connections sufficient to involve one or both party walls in the mechanism

(25)

2.2.5 Overturning of a wall connected to a perpendicular wall

The overturning of the façade in case of effective connection damages the orthogonal walls with a variable angle with the masonry quality: 

- a) good quality masonry (angle 30° and 45°), 
- b) average quality (15° and 30°); 
- c) low quality (0° and 15°)

2.2.6 Partial overturning

One side effective constraints to party wall

(25)

2.2.7 Out of plane damage due to the detachment of the transversal wall
2.2.8 Corner overturning (mix mechanism)

One free corner (isolated building or end/corner building in a row/group)

2.2.9 Out-of-plane collapse of a wall subjected retaining actions (vertical arch mechanism)
Vertical arch mechanism due to presence of ties or ring beams at the top of the wall

2.2.10 Arch effect in the thickness of the wall: ultimate condition for compressive failure in the section (vertical)

2.2.11 Arch effect in the thickness of the wall: ultimate condition for abutments overturning (vertical)

2.2.12 Out-of-plane bending of load bearing walls (for adobe buildings)

This type of damage to earthen buildings cracks the load bearing walls, but leaves the walls stable.
2.2.13 Slippage between walls and wood framing (for adobe buildings)

Roof, ceiling, and floor framing often slips at the interface with the adobe walls due to inadequate connection to the adobe walls. Horizontal upper-wall cracks: horizontal cracks may develop near the tops of walls when there is a bond beam or the roof is anchored to the beam.

2.2.14 Moisture damage contributions to instability (for adobe buildings)

Out-of-plane instability (or a contribution to instability) is caused by weakening or erosion, usually at the base, or saturation or repeated wet/dry cycles resulting in weakened slip-planes at the base of the wall along which the wall can slip and collapse.

2.2.15 Corner damage (for adobe buildings)

Damage often occurs at the comers of buildings due to the stress concentrations that occur at the intersection of perpendicular walls. Instability of corner sections often occurs because two sides of the corner are unrestrained. Therefore, the corner section is free to collapse outward from the building.

2.3 KINEMATICS MODELS FOR OUT-OF-PLANE MECHANISMS - HORIZONTAL STRIPS

2.3.1 Fixed beam mechanism
Horizontal arch mechanism of wall with large span and little or no restraint from internal walls

2.3.2 Arch effect in the thickness of the wall: ultimate condition for masonry crushing (horizontal)

2.3.3 Arch effect in the thickness of the wall: abutments overturning (horizontal)

2.4 PORCH, LODGE, ARCADE OR COLONNADE

2.4.1 Local damages
(see 3.2.2.3 and 3.1.6.1)

Cracks in transversal arches.
### 2.4.2 Soft storey

(25)

### 2.4.3 Local damages to pillars or columns due to bending action
(see 3.2.2.4 and 3.1.6.2)

(26)

Vertical cracks at the base of pillars or columns in the compressed side and horizontal cracks in the tensioned side.

### 2.4.4 Local damages to stone blocks columns or pillars due to bending action
(see 3.2.2.4 and 3.1.6.2)

Drum shifting and/or rocking and overturning

### 2.4.5 Damages of pillars or columns due to long term compressive actions
(see 3.2.2.5 and 3.1.6.3)

(26)

Vertical cracks in pillars or columns.

### 2.5 FLOORS AND VAULTS

Damage based selection of technologies

D3.1 – ANNEX 1
### 2.5.1 Head beams hammering
(see 3.1.5.1 and 3.3.4.1)

![Diagram of head beams hammering](image1)

### 2.5.2 Vault or floor local collapses
(see 3.2.2.6, 3.2.4.3, 3.2.7.3, 3.2.9.3 and 3.1.5.2)

![Diagram of vault or floor local collapses](image2)

### 2.5.3 Vaults damage due to spring rotation
(see 3.2.2.6, 3.2.4.3, 3.2.7.3, 3.2.9.3 and 3.1.5.3)

![Diagram of vaults damage due to spring rotation](image3)

Cracks in the vaults or detachment between the arches and/or the side walls.

### 2.5.4 Vaults damage due to in plane deformation
(see 3.2.2.7, 3.2.4.3, 3.2.7.3, 3.2.9.3 and 3.1.5.4)

![Diagram of vaults damage due to in plane deformation](image4)

Cracks in the vaults or detachment from the arches and/or the side walls.
### 2.5.5 Domes damage due to in plane deformation (for adobe buildings)

#### (30)

Hemispherical dome, with the bricks arranged radially and jointed by a clay-gypsum mortar. The cracks are usually localised in the mortar joints, therefore set concentrically, or seldom, oblique. The collapse are probably caused by the collapse of the supporting pillars or walls rather then to the structural ineffectiveness of the dome itself.

<table>
<thead>
<tr>
<th>Diagram</th>
<th>Description</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td>Dome typology with pendentives laid on the median axes of the sides and bricks arranged in inclined arched courses. The structural behaviour is ineffective, since the four segments of the dome are badly jointed to each other and the brick courses intersect each other at right angle at the median axes, causing local weakness and damage concentration. In case of earthquake the cracks are concentrated where in the courses line changes and, in highly damaged cases, along the diagonals as well.</td>
</tr>
<tr>
<td><img src="image2.png" alt="Diagram" /></td>
<td>Domes with pendentives laid down parallel to the supporting walls. The damage localisation is along the diagonals, close to the pendentives joints, where the bricks courses change the alignment angle. In the most damaged cases cracks along the median axes but also parallel to the supporting walls are visible.</td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram" /></td>
<td>Domes with isolated pendentives characterised by two weaknesses. The first is related to the courses discontinuity close to the diagonals. The second is along the medians of the vault, where the pendentives are completely isolated to each other due to the joint alignment in this position, even if they have parallel brick courses. This building solution, very vulnerable, is apparently incomprehensible and it is difficult to find a clear explanation. The first cracks are concentrated along the median axes, as a result of ineffectiveness of the joint connections. In the most damaged cases cracks along the diagonals and parallel to the median axes are documented.</td>
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<td>Section</td>
<td>Details</td>
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<tr>
<td><strong>2.6 STAIRS</strong></td>
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<tr>
<td><strong>2.6.1 Stairs damage</strong></td>
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<td><img src="image" alt="Stairs damage image" /></td>
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<tr>
<td><strong>2.7 ROOF</strong></td>
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<td><strong>2.7.1 Truss damage / movement / rotation (global or limited to some elements)</strong></td>
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<td></td>
<td><img src="image" alt="Truss damage image" /></td>
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<tr>
<td><strong>2.7.2 Roof covering damage</strong></td>
<td>Movement or lack of tiles or other covering elements.</td>
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<td><img src="image" alt="Roof covering damage image" /></td>
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<tr>
<td><strong>2.7.3 Overturning of tympanum spandrels</strong></td>
<td>V-shaped cracks near the façade corner and expulsion of the corner.</td>
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<tr>
<td></td>
<td><img src="image" alt="Tympanum spandrels image" /></td>
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</tbody>
</table>
### 2.8 FOUNDATIONS

#### 2.8.1 Lateral settlement

Cracks usually concentrated in the spandrels or in masonry discontinuity.

#### 2.8.2 Central settlement

Cracks usually concentrated in the spandrels or in masonry discontinuity.
3 DAMAGE DUE TO THE BUILDING TYPOLOGY

3.1 ABACUS OF COLLAPSE MECHANISMS OF ISOLATED BUILDINGS, PALACES, ROW-BUILDINGS OR AGGREGATE BUILDINGS

3.1.1 OUT OF PLANE MECHANISMS

3.1.1.1 Global overturning of the façade

Separation of the façade from the lateral walls, in proximity to the corner or with inclined cracks in the lateral walls. Evident out of plumb.

3.1.1.2 Partial overturning of the wall with rotations axis at the floor level

Overturning of the wall, with horizontal or V-shaped cracks. Separation of the masonry leaves or shift of the tie-beam.
3.1.1.3 Partial overturning of the wall with vertical strips subdivision

Partial overturning of the wall, with vertical cracks near the windows. Other cracks or bulging.

3.1.1.4 Partial overturning of the wall with corner expulsion
(see 5.2.3)

V-shaped cracks near the façades corner.
3.1.1.5 Partial overturning of the wall with diagonal rotation axis

Partial overturning of the wall, with cracks near the windows.
Other cracks or bulging.

3.1.1.6 Local overturning of the wall at roof level
(see 5.2.5)

Cracks near the head of wooden beams.
Sliding of the tie beams.
Significant displacement of the covering.

Partial overturning of the wall in the presence of r.c. tie beam.
Detachment between tie-beams and masonry.
Partial overturning of the wall in the presence of r.c. tie beam.
Detachment between tie-beams and masonry.

3.1.1.7 Local deformation at the floor level of the façade partially restrained

Local deformation or bulging at the floor level

3.1.1.8 Local overturning of the wall due to tie beam hammering
(see 5.2.2)

Floor shifting and local wall overturning (presence of tie beam).

3.1.1.9 Crack or local expulsion due to masonry discontinuities or repair

A- Local expulsion
Permanent rotation or displacement.
Cracks around the perimeter of the local repair or the discontinuity (e.g. infilled openings, chimney flues, etc.)

B- Cracks relates to the construction phases
Cracks around the boundaries of the construction phases.
Expulsion of the different masonry.
### 3.1.1.10 Local beam hammering

Local cracks and/or local expulsion at the floor level near the head of wooden beams.

### 3.1.1.11 Projections damage

Permanent rotation or displacement. Cracks around the elements.
3.1.2 IN PLANE MECHANISMS

3.1.2.1 Shear cracks of the piers

Diagonal cracks.

3.1.2.2 Shear cracks of the spandrels

Diagonal cracks in the spandrels

3.1.2.3 Flexural cracks of the piers (a) or of the spandrels (b)

Flexural cracks of the piers (a) or of the spandrels (b).

3.1.3 MIXED MECHANISMS

3.1.3.1 Shear cracks of the piers and local overturning of the orthogonal walls

V-shaped cracks and local overturning of orthogonal walls.
3.1.4 INTERNAL WALLS

3.1.4.1 Shear cracks of the internal walls

Diagonal cracks at the inside partition wall.

3.1.5 FLOORS AND VAULTS

3.1.5.1 Head beams hammering
(see 2.5.1 and 3.3.4.1)

3.1.5.2 Vault or floor local collapses
(see 2.5.2, 3.2.2.6, 3.2.4.3, 3.2.7.3 and 3.2.9.3)

3.1.5.3 Vaults damage due to spring rotation
(see 2.5.3, 3.2.2.6, 3.2.4.3, 3.2.7.3 and 3.2.9.3)

Cracks in the vaults or detachment between the arches and/or the side walls.

3.1.5.4 Vaults damage due to in plane deformation
(see 2.5.4, 3.2.2.7, 3.2.4.3 and 3.2.7.3, 3.2.9.3)

Cracks in the vaults or detachment from the arches and/or the side walls.
3.1.6 PORCH, LODGE, ARCADE OR COLONNADE

3.1.6.1 Local damages
(see 2.4.1 and 3.2.2.3)

(3)

Cracks in transversal arches.

3.1.6.2 Local damages to pillars or columns due to bending action
(see 2.4.3, 2.4.4 and 3.2.2.4)

(26)

Vertical cracks at the base of pillars or columns in the compressed side and horizontal cracks in the tensioned side.

3.1.6.3 Damages of pillars or columns due to long term compressive actions
(see 2.4.4 and 3.2.2.5)

(26)

Vertical cracks in pillars or columns.
3.2 ABACUS OF COLLAPSE MECHANISMS OF CHURCHES

3.2.1 FAÇADE

3.2.1.1 Overturning of the façade

Separation of the façade from the lateral walls, in proximity to the corner or with inclined cracks in the lateral walls. Evident out of plumb.

3.2.1.2 Overturning of the gable

Overturning of the gable, with horizontal (a) or V-shaped (b) cracks.
Local separation of masonry leaves or shifting of tie-beams.
Rotation of the trusses.

3.2.1.3 Shear mechanisms in the façade plane

Cracks in the façade with X-shaped shear cracks.
Central vertical crack or arched cracks near the corner (rotation).
Other cracks or bulging.
### 3.2.1.4 Displacement in the façade plane

Vertical cracks in the façade middle.
Rotation in the side walls.

### 3.2.1.5 Expulsion of the façade corner

V-shaped cracks near the façade corner.

### 3.2.1.6 Narthex

Cracks on the arches or in the trabeation due to columns rotation.
Detachment from the façade.
Local hammering.

### 3.2.2 HALL

#### 3.2.2.1 Permanent lateral displacement of the nave

Cracks in the arches and vaults.
Rotation of the lateral walls.
Out of plumb and cracks at the column/pillar bases due to flexural actions during the earthquake.
### 3.2.2.2 Overturning of the façade and damages to the orthogonal nave walls or arcades

![Overturning of the façade](image)

Typical mechanism of churches with nave and aisles.
Rotation of the pillars near the façade.

### 3.2.2.3 Longitudinal behaviour of the central nave

(see 2.4.1 and 3.1.6.1)

![Longitudinal behaviour](image)

Cracks in the arches.
Diagonal shear cracks in the aisle vaults.

### 3.2.2.4 Local damages to pillars or columns due to bending action

(see 2.4.2, 2.4.3 and 3.1.1.2)

![Local damages](image)

Vertical cracks at the base of pillars or columns in the compressed side and horizontal cracks in the tensioned side.

### 3.2.2.5 Damages of pillars or columns due to long term compressive actions

(see 2.4.4 and 3.1.6.3)

![Long term compressive](image)

Vertical cracks in pillars or columns.
### 3.2.2.6 Vaults of the hall or central nave
(see 2.5.2 and 2.5.3)

| (1) | Cracks in the vaults of the central nave. Detachment of the vaults from the arches and/or the side walls. |

### 3.2.2.7 Vaults of the side aisles
(see 2.5.4)

| (1) | Cracks in the vaults or detachment from the arches or the side walls. |

### 3.2.3 SIDE WALLS

#### 3.2.3.1 Overturning of the side walls

| (2) | Overturning of the side wall, with horizontal and V-shaped cracks in the orthogonal walls. |

#### 3.2.3.2 Shear mechanisms in the side walls

| (1) | Diagonal cracks (single or crossed) in masonry. The crack position and geometry is often influenced by wall discontinuity or opening |

#### 3.2.3.3 Expulsion of the walls corner

| (2) | V-shaped cracks near the façade corner. |
### 3.2.4 TRANSEPT

#### 3.2.4.1 Overtaking of the transept façades

Detachment of the wall from the lateral walls. Overturning or displacement of the gable.

![Diagram of transept façades](image)

#### 3.2.4.2 Shear mechanisms in the transept walls

Diagonal cracks (single or crossed). Cracks often related to wall discontinuity.

![Diagram of shear mechanisms](image)

#### 3.2.4.3 Vaults of transept

(see 2.5.2, 2.5.3 and 2.5.4)

Cracks in the vaults or detachment from the arches and/or the side walls.

![Diagram of vaults](image)

### 3.2.5 TRIUNPHAL ARCHES

#### 3.2.5.1 Triunphal arches

Formation of hinges in the arch, with sliding of ashlers. Out of plumb and cracks at the pillar bases due to bending actions during the earthquake.

![Diagram of triunphal arches](image)
### 3.2.6 DOME

#### 3.2.6.1 Dome, drum and tiburio

<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Dome Diagram" /></td>
<td>Cracks in the drum or to the main arches.</td>
</tr>
</tbody>
</table>

#### 3.2.6.2 Dome lantern

<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image2" alt="Dome Lantern Diagram" /></td>
<td>Cracks to the smaller dome in the lantern. Rotation or displacement of the piers.</td>
</tr>
</tbody>
</table>

### 3.2.7 APSE

#### 3.2.7.1 Overturning of the apse

<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3" alt="Apse Diagram" /></td>
<td>Vertical or inclined cracks in the walls of the apses. Vertical cracks in polygonal apses. U-shaped cracks in semi-circular apses. Vertical cracks in correspondence of the windows.</td>
</tr>
</tbody>
</table>

#### 3.2.7.2 Shear mechanisms in the apse

<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4" alt="Apse Shear Mechanism Diagram" /></td>
<td>Diagonal cracks (single or crossed). Cracks often related to wall discontinuity</td>
</tr>
</tbody>
</table>
### 3.2.7.3 Vaults of the presbytery or apse
(see 2.5.2, 2.5.3 and 2.5.4)

| (1) | Cracks in vaults or detachment from arches or side walls. |

### 3.2.7.4 Expulsion of the apse corner

| (2) | V-shaped cracks near the façade corner. |

### 3.2.8 ROOF

#### 3.2.8.1 Hammering and damage of the roof: hall

| (1) | Cracks near the head of wooden beams.  
Sliding of the beams.  
Detachment of r.c. tie beam and masonry.  
Detachment between tie-beams and masonry.  
Significant displacement of the roof covering. |

#### 3.2.8.2 Hammering and damage of the roof: transept

| (1) | Cracks near the head of wooden beams.  
Sliding of the beams.  
Detachment of r.c. tie beam and masonry.  
Detachment between tie-beams and masonry.  
Significant displacement of the roof covering. |
3.2.8.3 Hammering and damage of the roof: apse and presbytery

(1) Cracks near the head of wooden beams. Sliding of the beams. Detachment of r.c. tie beam and masonry. Detachment between tie-beams and masonry. Significant displacement of the roof covering.

3.2.9 SIDE AISLES

3.2.9.1 Overturning of the side aisles

(1) Overturning and possible detachment of the end wall from the side walls.

3.2.9.2 Shear mechanisms in the side aisles

(1) Diagonal cracks (single or crossed). Cracks often related to wall discontinuity

3.2.9.3 Vaults of the side aisles

(see 2.5.2, 2.5.3 and 2.5.4)

(1) Cracks in the vaults or detachment from the walls.
### 3.2.10 INTERACTIONS BETWEEN THE BUILDINGS

#### 3.2.10.1 Interactions between elements of different stiffness

1. The cracks are often caused by the discontinuity.
2. Cracks at the boundary of the volumes due to hammering.

#### 3.2.10.2 Overturning of the projections - veil, gable belfry, spires, pinnacles, statues

(see 3.2.2.1)

1. Global permanent rotation or displacement.
2. Cracks at the base of the elements due to the overturning.

### 3.2.11 BELL TOWER

#### 3.2.11.1 Bell tower

(see from 3.3.1.1 to 3.3.1.10 and 3.3.4.1)

1. Cracks next to the connection between the bell tower and the church due to local hammering or change of stiffness.
2. Shear cracks or sliding.
3. Vertical or inclined cracks (bulging of one or more corners).

#### 3.2.11.2 Belfry

(see 3.3.3.1 and 3.3.3.2)

1. Cracks in the arches.
2. Rotation and sliding of the piers.
### 3.3 ABACUS OF COLLAPSE MECHANISMS OF TOWERS AND BELL TOWERS

#### 3.3.1 BELL TOWER OR TOWER

##### 3.3.1.1 Shear cracks or sliding
(see 3.2.11.1)

Vertical cracks of the sidewalls of the tower and possible rotation of the angular piers of the belfry.

##### 3.3.1.2 Corner expulsion
(see 3.2.11.1)

Vertical or v-shapes cracks in one or more corners.

##### 3.3.1.3 Overturning of the bell tower top
(see 3.2.11.1)

Diagonal cracks in the four walls of bell tower. Lateral connections sufficient to involve one or both party walls in the mechanism. Overturning with two side wings (c). Partial overturning with one side wing. (d).
### 3.3.1.4 Shear/bending collapse
(see 3.2.11.1)

![Image of shear/bending collapse](image)

### 3.3.1.5 Horizontal arch mechanism
(see 3.2.11.1)

![Image of horizontal arch mechanism](image)

Horizontal arch mechanism of wall with large span and ineffective restraint or lack of restraint from the side walls.

### 3.3.1.6 In plane failure
(see 3.2.11.1)

![Image of in plane failure](image)

Sufficient level of connection to party wall on only one side.

### 3.3.1.7 Torsion
(see 3.2.11.1)

![Image of torsion](image)
### 3.3.1.8 Shifting of the bell tower top
(see 3.2.11.1)

Horizontal cracks. Unusually is related to stiffness changes due to adjacent volumes or of the building technology of the tower.

![Diagram of bell tower](image1.png)

### 3.3.1.9 Damages due to long term compressive actions
(see 3.2.11.1)

Vertical thin cracks. The damage can evolve with seismic bending actions.

![Diagram of cracks](image2.png)

### 3.3.1.10 Local damages at the base due to flexural action
(see 3.2.11.1)

Vertical cracks. Side compressive failure (b). Corner compressive failure (c).

![Diagram of damages](image3.png)
### 3.3.1.11 Foundation settlement (lateral or at corner)

![Diagram of foundation settlement](image)

### 3.3.2 PROJECTIONS

#### 3.3.2.1 Overturning of the projections - veil, gable belfry, spires, pinnacles, battlements, statues

(see 3.2.11.2)

![Diagram of projections](image)

- Global permanent rotation or displacement.
- Cracks at the base of the elements.

### 3.3.3 BELLFRY

#### 3.3.3.1 Piers

(see 3.2.11.2)

![Diagram of piers](image)

- Rotation and sliding of the piers, with local corner expulsion.
### 3.3.3.2 Cracks in the arches (see 3.2.11.2)

Formation of hinges in the arch, with sliding of stone ashlars. Out of plumb and cracks at the pillar bases due to horizontal actions during the earthquake.

![Cracks in the arches](image1)

### 3.3.4 FLOORS AND VAULTS

#### 3.3.4.1 Internal floor or vault collapse

![Internal floor or vault collapse](image2)

### 3.3.5 INTERACTIONS BETWEEN THE BUILDINGS

#### 3.3.5.1 Interactions between elements of different stiffness (see 3.1.11.1)

Vertical or diagonal cracks near the connection between the bell tower and the church or other adjacent buildings. The cracks start often from the wall discontinuities or from the openings.

![Interactions between elements of different stiffness](image3)
### 4 DAMAGE DUE TO INTERACTIONS BETWEEN BUILDING PORTIONS OR DUE TO IRREGULARITIES

#### 4.1 INTERACTIONS BETWEEN BUILDING PORTIONS

**4.1.1 In plane shifting**
(see 5.2.6)

<table>
<thead>
<tr>
<th>Diagram</th>
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</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td>Displacement caused by the floor stiffness changes, in general in correspondence to constructive discontinuity.</td>
</tr>
</tbody>
</table>

**4.1.2 Changes of stiffness due to irregularities in plan and height, often due to new additions**

<table>
<thead>
<tr>
<th>Diagram</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image2.png" alt="Diagram" /></td>
<td>Displacements and cracks caused by constructive discontinuity and new additions. Local hammering. Boundary cracks.</td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram" /></td>
<td></td>
</tr>
</tbody>
</table>

**4.1.3 Out of plane and in plane damages of new additions**

<table>
<thead>
<tr>
<th>Diagram</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4.png" alt="Diagram" /></td>
<td></td>
</tr>
</tbody>
</table>

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*Damage based selection of technologies*  
*D3.1 – ANNEX 1*
4.1.4 Hammering between adjacent cells

Displacements and cracks related to constructive discontinuity and historic phases.
Local hammering
Boundary cracks

4.1.5 Cell hammering through connection element

Vertical or diagonal cracks near the connection element.

4.2 MASONRY DISCONTINUITY

4.2.1 Partial rotation

Rotation of additions and crack concentration related to stiffness changes.
Possible corner expulsion.

4.2.2 Discontinuity of plan configuration

4.2.3 Different floors levels and building technology
4.3 OROGRAPHIC CONDITIONS

4.3.1 Overturning mechanism in building in slope

Change of stiffness or restraints due to the different ground level or small movement of the slope during the earthquake can trigger the overturning.
5 DAMAGE DUE TO THE REPAIR TECHNIQUES

5.1 TRADITIONAL REPAIR TECHNIQUES

5.1.1 Local deformation at the floor level of the façade partially restrained

(13) without tie-beam

(13) with tie-beam

5.1.2 Local deformation at the floor level of the façade partially restrained

(5)

(6) with tie-beam (without tie-beam see 3.3.1.7)
5.2 MODERN REPAIR TECHNIQUES

5.2.1 Out-of-plane mechanism in the presence of stiff and heavy roof structure - qualitative interpretation

(20) top of the wall

(20) near the windows
### 5.2.2 Local overturning of the wall due to tie beam hammering
(see 3.1.1.8)

- Floor shifting and local wall overturning (presence of tie beam).

### 5.2.3 V-shaped cracks near the façades corner – r.c. tie beam presence
(see 3.1.1.4)

### 5.2.4 Local damage due to the presence of r.c. tie beam

### 5.2.5 Partial overturning of the wall in presence of r.c. tie beam
(see 1.3.1.6)

### 5.2.6 In plane shifting caused by the presence of r.c. tie beam
(see 4.1.1)
5.2.7 Jacketing detachment due to the lack of connections

![Diagram and image of jacketing detachment due to the lack of connections](image)

(26)

5.2.8 Jacketing detachment with wall separation due to the lack of connections

![Diagram and image of jacketing detachment with wall separation due to the lack of connections](image)

(26)

5.2.9 Low durability of jacketing due to insufficient thickness of the cover with consequent steel net corrosion

![Image of low durability of jacketing](image)

(26)

5.2.10 Local damage due to the lack of net overlapping

![Image of local damage due to the lack of net overlapping](image)

(26)
6 REFERENCES


(3) DCP 2006, Department of Civil Protection and Ministry of Cultural Heritage, (2006), Damage assessment record for cultural heritage - damage to palaces, Italian

(4) CNR-ITC, Repertorio dei meccanismi di danno, delle tecniche di intervento e dei relativi costi negli edifici in muratura, Ricerca svolta nell’ambito di una convenzione tra Regione Marche, Università degli Studi dell’Aquila e CNR-ITC, (in Italian).


(25) UBATH contribution

(26) POLIMI contribution


(29) BAM-ZRS contribution (see D3.1_Annex 2.2_BAM-ZRS_a)


