International Seminar

Assessment and improvement of structural safety under seismic actions of existing constructions: Reinforced Concrete Structures and Historical buildings

SCE - Shamoon College of Engineering, Beer Sheva - 29 November 2015
International Conservation Center, Citta' di Roma, Old Acre - 1 December 2015

Investigation methodologies and techniques: historical investigations, surveys, in-situ and laboratory tests, monitoring

Prof. Maria Rosa Valluzzi

University of Padova, Department of Cultural Heritage
mariarosa.valluzzi@unipd.it
Existing buildings are affected by many uncertainties concerning various aspects detectable with diagnosis investigations:

- Geometry
- Materials
- Structural system and configuration (conceptual design)
- Structural component typology
- Constructive details
- Effect of deterioration and damage
- Influence of interventions
- Interaction with soil

Preservation of historic buildings:
- In-situ low-obtrusive procedures
- Combination of techniques for cross-checking (complementarity)

Objectives:
- Improve knowledge
- Minimize interventions
- Calibration and validation of assessment models
Iscarsah Guidelines - Recommendations for the analysis, conservation, and structural restoration of architectural heritage

This knowledge can be reached by:

- description of the structure’s geometry and construction;
- definition, description and understanding of building’s historic and cultural significance;
- description of the original building materials and construction techniques;
- historical research covering the entire life of the structure including both changes and any previous structural interventions;
- description of the present state including identification of damage, decay and possible progressive phenomena, using appropriate types of test;
- description of the actions involved, structural behaviour and types of materials;
- a survey of the site, soil conditions and environment of the building.
Italian Standard & Guidelines – Building knowledge

The **knowledge of the masonry historical building**, using particular techniques of analyses and interpretation, is the basis for a reliable appraisal of the seismic safety and for the choice of an effective improvement.

Steps:

- Building identification
- Functional characterisation of the building
- Geometrical survey
- Historical analyses of events and past interventions
- Material and structural survey and conservation state
- Mechanical characterization of materials
- Ground and foundations
- Monitoring

Different knowledge levels and confidence factors CF
Monitoring allows to evaluate the behaviour of the structure during its life, enabling the scheduling of maintenance works, and indicating the possible necessity of strengthening or repair interventions.

Monitoring start with basic visual inspection, to evaluate macroscopic changes in the structure (damage pattern onset, widening of existing cracks...), up to more sophisticated electronic controls on significant mechanical or physical parameters.
To evaluate the capacity of structural elements, the **material properties** have to be divided by the **confidence factor**, obtained on the basis of the gained **level of knowledge**: an higher knowledge level means higher mechanical properties that can be considered for the materials.

If the considered model for seismic safety assessment does not consider mechanical properties of the material, the confidence factor is used to **reduce the acceleration corresponding to the particular limit state**.

The **confidence factor** is determined as:

\[ F_C = 1 + \sum_{k=1}^{4} F_{Ck} \]

<table>
<thead>
<tr>
<th>Geometrical survey</th>
<th>Material and constructive details inspection</th>
<th>Materials mechanical properties</th>
<th>Ground and foundations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full geometrical and structural survey ( F_{C1} = 0.05 )</td>
<td>Limited material and constructive details on site inspection ( F_{C2} = 0.12 )</td>
<td>mechanical properties obtained from old data ( F_{C3} = 0.12 )</td>
<td>Limited inspections on ground and foundation, absence of geological data ( F_{C4} = 0.06 )</td>
</tr>
<tr>
<td>Full geometrical and structural survey, with crack and deformation patterns ( F_{C1} = 0 )</td>
<td>Extended material and constructive details on site inspection ( F_{C2} = 0.06 )</td>
<td>Limited on site testing on material mechanical properties ( F_{C3} = 0.06 )</td>
<td>Limited inspections on ground and foundation, presence of geological data ( F_{C4} = 0.03 )</td>
</tr>
<tr>
<td></td>
<td>Comprehensive material and constructive details on site inspection ( F_{C2} = 0 )</td>
<td>Extended on site testing on material mechanical properties ( F_{C3} = 0 )</td>
<td>Extended and comprehensive inspections on ground and foundation ( F_{C4} = 0 )</td>
</tr>
</tbody>
</table>
To carry out the structural analyses, it is necessary to gain **proper knowledge** by means of surveys, historical researches, in-situ and laboratory tests:

- **Building Geometry**
  - geometry, particular elements (such as chimneys, niches, etc), crack pattern & out of plumbs
  - by means of surveys

- **Constructive Details**
  - connections, lintels, elements to counteract thrusts, vulnerable elements, masonry typology
  - limited *in situ inspection*
  - extended & comprehensive *in situ inspection*

- **Material Properties**
  - particularly aimed at the mechanical characterization of masonry, through inspections, NDT, MDT & DT
  - limited *in situ testing* (inspections)
  - extended *in situ testing* (MDT & NDT)
  - comprehensive *in situ testing* (DT)
INVESTIGATION PLAN

1. HYPOTHESES ON THE BUILDING EVOLUTION
2. IDENTIFICATION OF PLAN-ELEVATION CHARACTERISTICS
3. INTERPRETATION OF CRACK AND DEFORMATION PATTERNS
4. IDENTIFICATION AND CHARACTERIZATION OF CONSTRUCTION DETAILS/ELEMENTS
5. MASONRY TYPOLGY
6. MATERIALS CHARACTERIZATION

IDENTIFICATION OF RESISTING STRUCTURAL SCHEME, DEFINITION OF ACTIONS AND MECHANICAL PARAMETERS
HISTORIC SURVEY
Geometrical survey includes: survey at each floors of all masonry elements and eventual niches, voids, chimneys, vault survey, floors, roofing, stairs, definition of loads, foundations.
Survey and drawing of crack and deformation patterns
CONSTRUCTION DETAILS

- quality of connections between walls;
- type and quality of connections between horizontal diaphragms and walls;
- type and efficiency of lintels above openings;
- presence and efficiency of elements to counteract horizontal thrusts;
- presence of structural or non structural elements with high vulnerability;
- type and quality of masonry
The critical analysis is carried out by means of visual inspections, by removing plaster and small masonry dismantling, in order to check both masonry texture and masonry in its thickness, considering also the connections between walls and between walls and floors.

*Limited on-site verifications*: based on visual surveys, usually through tests on the masonry that lead to superficial examination

*Extended and comprehensive on-site verifications*: based on visual surveys, usually through tests on the masonry that lead to both superficial and deep examination, and of the connection between orthogonal walls.
It is possible to refer to abaci for the evaluation of the quality and bearing capacity of masonry typologies.

Heterogeneous masonry built up with poor materials, presence of voids, irregularities, multi-leaf sections, absence of connections.

Out-of-plane brittle collapses

Survey forms: frequent local masonry typologies.
MASONRY TYPOLOGIES

Montesanto di Sellano (PG) - Politecnico di Milano

Regular texture

Texture with sub-horizontal courses

Irregular texture
MASONRY MORPHOLOGY

TWO-LEAF WALLS

Progetto esecutivo Reluis 2005-2008; Allegato 3b.1_UR06_2
MASSONRY MORPHOLOGY

THREE-LEAF WALLS

Progetto esecutivo Reluis 2005-2008; Allegato 3b.1_UR06_2
MASONRY QUALITY EVALUATION

Local constructive rule parameters:

- mortar quality
- presence of transverse connecting elements
- elements shape
- elements dimension
- staggering vertical joints
- horizontality of the courses
- units strength
- wedges

(University of Perugia)
Local dismantling and reconstruction of the inner morphology of the wall

(Binda, 2011)
EXPERIMENTAL TEST PROCEDURES

EXPERIMENTAL TESTS

on-site

Qualitative tests
- Historical investigations
- Survey of the crack outline
- Moisture
- Other NDT (sonic tests, radar, thermograph, etc)

Quantitative tests
- Geometric survey
- Monitoring and control of the structure
- Measurements of the local stress state (flat jacks, etc.)

laboratory

Sampling

Chemical tests
Physical tests
Mechanical tests

Input parameters for the calculation models

Evaluation of the bearing capacity of the structure

Qualitative and quantitative data: geometric and mechanic parameters

( binda, 1994)
Destructive Tests provide direct information on the mechanical properties of materials. Nevertheless, the main problem is the obtrusiveness of the investigation procedure.

Non-Destructive Tests are indicated as a complement to Destructive / Medium Destructive Tests. The combined use of NDT and DT / MDT and the cross-check of the results can induce more "quantitative" significance to the NDT results, through a calibration at local level.

NDT tests extended in large areas may address MDT for the best optimization of the experimental campaign and the exploitation of the resources, to improve the knowledge of the structure.
INNER INSPECTIONS AND TESTING ON SAMPLES

Local dismantling for direct visual inspection
Sampling for lab tests

(Politecnico di Milano)
**INVESTIGATION METHODS FOR MASONRY BUILDINGS**

**INVESTIGATIONS ON MATERIALS**

**INVESTIGATIONS ON MASONRY**

**MONITORING AND CONTROL OF THE STRUCTURES**

- **Destructive tests**
  - Laboratory: mono-axial direct compression, diagonal compression, shear-compression
  - On-site:
    - direct inspections, endoscopies, core boring
    - single flat jacks
    - double flat jacks
    - shove test
    - pull-out test
    - dilatometer

- **Minor destructive tests (MDT)**

- **Non-destructive tests (NDT)**
  - passive:
    - surveys and maps
    - pictures
    - displacements measurements
    - spontaneous phenomena (magnetometers)
  - active:
    - sonic and ultrasonic tests
    - radiography, georadar
    - thermographs
    - sclerometer
    - dynamic tests
Direct evaluation of mechanical properties

- strength
- deformability

- compression
- shear
- elastic modulus
- shear modulus
- Poisson coefficient

UNIAXIAL COMPRESSION

DIAGONAL COMPRESSION

SHEAR-COMPRESSION
Strength of masonry walls: compression

Mechanical properties of the original masonry and after consolidation interventions (E, ν, f_m) through experimental tests

(Bettio, Modena 1993)

On-site

Laboratory
The compression behavior shows the differences in terms of resistances and stiffness brought from different kinds of intervention.
DESTRUCTIVE TESTS

On site compression and shear

On site diagonal-compression

DS-D1 [mm]  H [kN]

Envelope

Idealized

Experiment

Ke=197.5 kNmm
Hu=110 kN
du=7.34
DESTRUCTIVE TESTS

Mechanical properties of the original masonry and after consolidation interventions ($\tau_0, G$) with experimental tests
MINOR DESTRUCTIVE TESTS

- **INVESTIGATIONS ON MATERIALS**
  - Destructive tests
    - Laboratory
      - mono-axial direct compression
      - diagonal compression
      - shear-compression
    - On-site
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- **MONITORING AND CONTROL OF THE STRUCTURES**
  - Non-destructive tests (NDT)
    - passive
      - • sonic and ultrasonic tests
      - • radiography, georadar
      - • thermographs
      - • sclerometer
      - • dynamic tests
    - active
CORING

To understand the morphology of a masonry wall it is important a **direct inspection**. Sometimes it could be performed by removing few bricks or stones. **Coring** is commonly done with a rotary driller using a diamond cutting edge. A small camera may be inserted into the borehole allowing a detailed study of its surface and try a reconstruction of the wall section.

Drilled core and reconstruction *(Binda, 2000)*

Other slightly destructive tests are:
- the **penetration tests** proposed in different ways, like probes, drillers, etc. correlate the depth of penetration to the mortar mechanical properties;
- the **pull-out tests** can only be used on bricks and stones
- the **dilatometer** can give deformability properties of inner cores
SINGLE FLAT JACK TEST

The determination of the state of stress is based on the stress relaxation caused by a cut perpendicular to the wall surface; the stress release is determined by a partial closing of the cutting, i.e. the distance after the cutting is lower than before. A thin flat-jack is placed inside the cut and the pressure is gradually increased to obtain the distance measured before the cut.

The equilibrium relationship is the fundamental requirement for all the applications where the flat-jack are currently used (ASTM, 1991):

\[ S_f = K_j K_a P_f \]

- \( S_f \) = calculated stress value
- \( K_j \) = jack calibration constant (<1)
- \( K_a \) = slot/jack area constant (<1)
- \( P_f \) = flat-jack pressure

Single flat-jack test (detection of state of stress) carried out at the Monza Tower (Binda, 1998)
DOUBLE FLAT JACK TEST

The test described can also be used to determine the **deformability characteristics** of a masonry. A second cut is made, parallel to the first one and a second jack is inserted, at a distance of about 40 to 50 cm from the other. The two jacks delimit a masonry sample of appreciable size to which a uni-axial compression stress can be applied.

Double flat-jack test (stress-strain behaviour) on West side of the Monza Tower (Binda, 1998)
INVESTIGATIONS ON MATERIALS

Destructive tests

Laboratory
- mono-axial direct compression
- diagonal compression
- shear-compression

On-site
- direct inspections, endoscopies, core boring
- single flat jacks
- double flat jacks
- shove test
- pull-out test
- dilatometer

INVESTIGATIONS ON MASONRY

Minor destructive tests (MDT)

MONITORING AND CONTROL OF THE STRUCTURES

Non-destructive tests (NDT)

Laboratory
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active
- sonic and ultrasonic tests
- radiography, georadar
- thermographs
- sclerometer
- dynamic tests
NDT can be helpful in finding hidden characteristics (internal voids and flaws and characteristics of the wall section) which cannot be known otherwise than through destructive tests.

**BOREHOLE VIDEO-ENDOSCOPY**

Usually integrate the coring inspection in order to detect the morphology of the wall section (or the structural component – also floors, roof, etc..), thickness, presence of voids, cracking, the effectiveness of interventions (e.g., injections), etc.
SONIC PULSE VELOCITY TEST

The use of sonic tests has the following aims:
- to qualify masonry through the morphology of the wall section;
- to detect the presence of voids and flaws;
- to find crack and damage patterns;
- to control the effectiveness of repair by injection technique.
SONIC TEST: qualitative evaluation for masonry morphology and effectiveness of intervention (injections)

(Binda, 2000)
SONIC TEST

The velocity and waveform of stress waves generated by mechanical impacts can be affected by:

- Input frequency generated by different types of instrumented hammers and transducers;
- Number of mortar joints crossed from the source to the receiver location: the velocity tends to decrease with the number of joints;
- Local and overall influence of cracks.

Local and overall influence of cracks: sonic tests on a pillar of the church of SS. Crocifisso in Noto - SR (Binda, 1999)
Flat jack tests: some results obtained with single and double flat-jack tests on the external wall of a church, of a bell tower and of a civil building in Campi Alto di Norcia (PG)

Sonic tests: representative results of the diagonal surface sonic measurements on the same walls
GEORADAR

When applied to masonry, the applications of radar procedures can be the following:

- to locate the position of large voids and inclusions of different materials, like steel, wood, etc.;
- to qualify the state of conservation or damage of the walls;
- to define the presence and the level of moisture;
- to detect the morphology of the wall section in multiple leaf masonry.
NON DESTRUCTIVE TESTS

Detector of ferromagnetic materials

Detection of metals inside materials (ferromagnetic materials) – usually used as covermeter.

Eddy current principle: the induced magnetic field is dissipated when meets a conductive material.
Surface hardness methods are based on the relation between the surface hardness and the compressive strength of material (concrete), selection of pointing mortars or quality control (masonry).

<table>
<thead>
<tr>
<th>Class</th>
<th>Hardness</th>
<th>Indicative quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (zero)</td>
<td>&lt;15</td>
<td>Very soft</td>
</tr>
<tr>
<td>A</td>
<td>15-25</td>
<td>Soft</td>
</tr>
<tr>
<td>B</td>
<td>25-35</td>
<td>Moderate</td>
</tr>
<tr>
<td>C</td>
<td>35-45</td>
<td>Normal</td>
</tr>
<tr>
<td>D</td>
<td>45-55</td>
<td>Hard</td>
</tr>
<tr>
<td>E</td>
<td>55</td>
<td>Very hard</td>
</tr>
</tbody>
</table>
THERMOVISION

The **thermographic analysis** is based on the thermal conductivity of a material and may be passive or active. The passive application analyses the radiation of a surface during thermal cycles. If the survey is active, forced heating to the surfaces analyzed are applied.

Thermovision can be very useful in diagnostic:
- to identify areas under renderings and plasters,
- to survey cavities,
- to detect inclusions of different materials,
- to detect water and heating systems,
- to detect moisture presence.
NON DESTRUCTIVE TESTS

THERMOVISION: Investigation in the Giotto’s Chapel (Padua)

(Grinzato et al., 2002)
NON DESTRUCTIVE TESTS

THERMOVISION:
detection of modifications due to interventions
detection of structural systems

<table>
<thead>
<tr>
<th>Label</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP01</td>
<td>38.1°C</td>
</tr>
<tr>
<td>SP02</td>
<td>37.5°C</td>
</tr>
<tr>
<td>SP03</td>
<td>36.9°C</td>
</tr>
</tbody>
</table>
NON DESTRUCTIVE TESTS

THERMOVISION:
Detection of texture and deterioration, thermal dispersion, humidity content
Dynamic tests on ties

\[ T = (f \ast \lambda)^2 \ast \mu \]
Dynamic identification tests

<table>
<thead>
<tr>
<th>Proprietà</th>
<th>E</th>
<th>1.2E+03</th>
<th>MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ρ</td>
<td>1.3E+03</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proprietà 2</th>
<th>E</th>
<th>3.2E+03</th>
<th>MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ρ</td>
<td>1.3E+03</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proprietà 3</th>
<th>E</th>
<th>1.2E+03</th>
<th>MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ρ</td>
<td>1.5E+03</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

Scena $f_1=3.44$ Hz
MONITORING AND CONTROL OF STRUCTURES

- **Continuous**
  - Measure of increasing parameters
  - Crack patterns, stress states, etc.

- **Discontinuous**
  - Measure of variation of parameters compared to a stationary state
  - Dynamic excitation, static loading, etc.

- **Static**
  - Measure of parameters related to quasi-static effects of actions
  - Displacement, deformations, stresses, temperature, cracks, out-of-plumb, tilting, damage, etc.

- **Dynamic**
  - Time-history measurement of vibrations
  - Accelerations, velocity, time-displacements

- **Periodic**
  - Measurement at regular time intervals

- **Permanent**
  - Measurement at very frequent time intervals

MONITORING SYSTEMS
MONITORING AND STRUCTURAL CONTROL

Cracks

Tilting

data-logger

Extensimeters

Heavy masses monitoring

Piezometers
MONITORING AND STRUCTURAL CONTROL

Example of monitoring: Palazzo della Ragione (Padova, XIII-XV cen.)

- Wind effect monitoring
- Stepped sine test
- FE modelling
- Modal identification
- On-line data management

Data acquisition

WWW database

Web monitoring home page

Modal Analysis

Example of monitoring: Palazzo della Ragione (Padova, XIII-XV cen.)

Data acquisition

WWW database

Web monitoring home page

Modal Analysis
Example of a monitoring system for the control of the behavior: Qutb Minar – New Delhi (India)

- Positioning of **sensors**:  
  1. acceleration transducers  
  2. temperature and R.H. sensor  
  3. displacement transducer  
  4. wind velocity and direction transducer  

- Data acquisition and analysis

0.62 Hz  1.96 Hz  3.82 Hz
Example of monitoring: Monza Bell Tower XVI cen.)
Monitoring of crack patterns

‘89-’ 97 trend
International Seminar

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University of Padova, Department of Cultural Heritage
mariarosa.valluzzi@unipd.it

THANKS FOR YOUR ATTENTION