Assessment and improvement of structural safety under seismic actions of existing constructions: Historic Buildings and R.C. Structures.

R.C. STRUCTURES:
LESSONS LEARNED FROM THE PAST EARTHQUAKES:
DAMAGE CATALOGUES AND INTERPRETATION

Prof. Eng. Claudio Modena claudio.modena@dicea.unipd.it

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Beer Sheva, Shamoom College
Seismic codes aims to provide performance-based guidance for design and assessment of structures.

The performance of the structure is defined in relation to “limit states”. Beyond the limit state condition the structure no longer meets the needs for which it was designed. There are two distinct levels of performance in seismic design:

- **Ultimate Limit State**: a seismic event with a return period many times greater than service life of the structure is considered; the structure should not collapse under ground shaking, but it may have sustained such a level of damage that it could not be possible to economically repair it following the earthquake. **Inelastic behaviour**

- **Serviceability Limit State**: a seismic event with a return period comparable to the service life of the structure is considered; there should be no damage requiring repair, and normal operations of the structure should not be significantly affected. **Elastic behaviour**
R.C. structures should exhibit an adequate (possibly great) capability of dissipate energy during inelastic response (DUCTILITY).

Energy dissipation should occur without a significant loss of RESISTENCE to both vertical and horizontal actions.

• **Elastic Stiffness:** \( k = \frac{F_y}{\Delta_y} \)
  Quantity that correlates displacements and forces of a structural element within linear-elastic limits. Stiffness is relevant in limiting structural damage caused by seismic events of low to medium intensity (small elastic displacements).

• **Resistance:** \( F_y \)
  Maximum force that a structural element (or the entire structure) can withstand responding elastically. Resistance is relevant in limiting structural damage caused by seismic events of low to medium intensity (inelastic response is prevented).

• **Ductility:** \( \frac{\Delta}{\Delta_y} \)
  Ratio between current displacement \( \Delta \) and yield displacement \( \Delta_y \). Ductility allows the structure to reach great displacements without collapsing (even though severe damage could occur).
Earthquake-resistant buildings

• Basic criterion for a building structure in a seismic zone is **REGULARITY**, intended both as **PLAN** and **ELEVATION REGULARITY**

• **REGULARITY** implies several requisites: **compactness**, **symmetry**, **uniformity**

• **PLAN REGULARITY** produce pure lateral motions
  – regular distribution of masses and lateral load resisting elements eliminates large eccentricities leading to torsional effects
  – to achieve plan regularity:
    • compactness and symmetry
    • avoid or limit plan set-backs
    • subdivide the building into separate independent units using seismic joints
    • strengthen those parts of the building that experience largest displacements/forces
Earthquake-resistant buildings

- **ELEVATION REGULARITY** implies that the first eigenmode is predominant and that eigenmodes shapes in both direction can be considered as linear
  - avoid sensitive zones where concentrations of stress or large ductility demands increase damage susceptibility
  - to achieve elevation regularity:
    - nearly constant stiffness and mass distributions
    - continuous bracings over total height
    - avoid interruptions of the lateral stiffness over height by e.g. soft stories
    - All lateral load resisting systems, such as cores, structural walls, or frames, shall run without interruption from their foundations to the top of the building or, if setbacks at different heights are present, to the top of the relevant zone of the building
• **Vertical lateral load resisting elements** shall give rise to
  - comparable lateral stiffnesses
  - evenly distributed horizontal forces resisting elements
  - symmetric distributed system of resisting elements in both directions

• In general the **positions of centre of gravity and centre of stiffness shall be coincident**: thereby building has only pure lateral motions and torsional effects are avoided
  - Centre of gravity position is determined by mass distribution
  - Centre of stiffness position is determined by plan position of lateral resisting elements (frames and walls)

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**Earthquake-resistant buildings**

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**Unsatisfactory systems**

**Desirable systems**
Earthquake-resistant buildings

- **Rigid diaphragms** for floor levels
- **Continuous load path** of horizontal forces down to the foundations.
- **Structural regularity** in mass, stiffness and resistance distribution to achieve
  - reduction of global *torsional effects*
  - reduction of local concentrations demands in terms of *resistance* or *capacity*
  - reduction of *soft storey collapse* probability
- **Redundancy** of structural elements, which permits
  - bending moment redistribution behaviour
  - to postpone structural collapse
- **Limited masses and adequate stiffness** to achieve low displacements and
  - reduction of second order effects
  - reduction of non-structural elements damage
- **Flexural collapse mechanism**
- **Absence of fragile failure modes** (*shear failure*)
The L’Aquila earthquake occurred the 6th April 2009 and was characterized by a Magnitude of 6.3 Mw.

Significant damages were observed to cultural heritage and residential buildings, in particular referring to framed structures, most of which designed according to the seismic code of the time of construction (late sixties-early seventies).
Accelerograms of 06/04/09 earthquake, l’ Aquila

Response spectra of L’ Aquila earthquake

Pseudo-acceleration response spectra (5% equivalent damping)

Factors influencing damage mechanisms in frame buildings

- Conceptual design
- Construction details
- Quality of materials

SOME EXAMPLES

Building close to Via XX Settembre, L’ Aquila
Hotel Duca degli Abruzzi, Via Giovanni XXIII (AQ)
Soft-Storey” mechanism – ground floor

Building in Pettino (AQ)
- Structural Damages Observed

"Soft-Storey” mechanism – ground floor
Soft-Storey” mechanism – upper floors

Building in Pianola (AQ)
Pounding of adjacent structures or insufficient joints

L’ Aquila, 2009
Pounding of adjacent structures or insufficient joints

L’Aquila, 2009
Asymmetric bracing and plan irregularity

Building in Pettino (AQ)
Asymmetric bracing and plan irregularity

L’Aquila, 2009
Asymmetric bracing and plan irregularity

L’Aquila, 2009

LIMITS OF THE EXISTING TOOLS FOR THE ANALYSIS OF STRUCTURAL RESPONSE TO STATIC AND DYNAMIC ACTIONS
Lack of “capacity design” in the conceptual design phase

Buildings in L’Aquila, (dx: Via Vicentini)
In-plane and out-of-plane damage to infill walls

Buildings in Pianola and L’Aquila
In-plane and out-of-plane damage to infill walls

- Structural Damages Observed

Masonry infills out-of-plane damages
In-plane and out-of-plane damage to infill walls

Masonry infills in-plane damages

Masonry infills out-of-plane damages
In-plane and out-of-plane damage to infill walls

- Infill in-plane Damages

Shear damages
Partially infilled frames

School building in via Duca degli Abruzzi, L’ Aquila

Friuli, 1976
Short-column effect

Stair in a building in L’ Aquila
Construction details and quality of materials

Building in Pianola (AQ)

foto Ferretti D.
Damage to structural joints and construction details

Buildings in and close by L’ Aquila
Damage to structural joints and construction details

- Structural Damages Observed

Steel bars instabilities
Construction details and quality of materials

Buildings in L’Aquila

Shear failure of column-of-beams, insufficient stirrups
Construction details and quality of materials

Damage to beam-column joints

Collaps due to failure of non-confined corner joint

Buildings in L’Aquila
Develop a site specific response spectrum!

Castelnuovo di San Pio delle Camere (AQ)
Damage to parapets, façade elements, ceilings, installations

Acqueduct in Paganica (AQ)

Residential buildings in Pianola (AQ)
Damage to parapets, façade elements, ceilings, installations

Buildings in L’ Aquila

Damage to parapets, façade elements, ceilings, installations

Buildings in L’ Aquila
INDUSTRIAL RC AND PRC BUILDINGS

Structural damages in the recent Emilia earthquake (20-29 May 2012)

http://www.reluis.it/ > Terremoto Emilia 2012 > rapporti tecnici
The recent earthquakes that struck the region of Emilia-Romagna in May 2012 revealed the enormous structural weaknesses of the industrial buildings and, more generally, the RC prefabricated buildings.

The construction systems typical of these structures (most of times of single-storey buildings) are characterized by isostatic schemes, free of redundancies, with floors without in-plane stiffness (no diaphragm action, in which the resistant function is reduced to a simple system of "inverted pendulum" represented by the single pillar.)
One-story industrial buildings typologies

Flat Roof (10-15%)

FLAT ROOF:
Main beams: I section, L=10-15m
Secondary beams: Double T, L=10-25m

Double slope (10-15%)

Double T beams

PRC HORIZONTAL STRUCTURES
RC AND PRC VERTICAL ELEMENTS

Period: 1960-2000

Double T beams

ATT rovesciati

ATT con lucernario

Main beams: I section, L=10-15m
Secondary beams: Double T, L=10-25m
Main beams:  
I section, L=10-15m

Secondary beams:  
Shed  
L=15-30m

Shed roof,  
Beam h=cost.  
L= 12-16m,  
i=6-15m  
Inclined roof = RC secondary beams with enlightments
One-story industrial buildings typologies

Cast on site structures

Period: 1930-60

Rc concrete-brick vaults

Shed
Multi-story industrial buildings typologies

Period: 1960-2000
PRC HORIZONTAL STRUCTURES
RC AND PRC VERTICAL ELEMENTS

TWO STORIES

Offices level

Typical main beam span: L=10-15m
Due livelli

Period: 1960-2000
PRC HORIZONTAL STRUCTURES
RC AND PRC VERTICAL ELEMENTS

Tre livelli

Tegoli TT
Deficiencies in prefabricated rc industrial buildings

Typical one-story systems, designed and dimensioned essentially for vertical loads only (modest horizontal actions-wind load), without redundancies.
The roof structure is not rigid (no possible forces redistribution due to diaphragm action), with prc horizontal secondary elements simple laid over beams, and beams connected with hinges to the column top.
The 3-d global system is reconducted to a series of simple "inverted pendulum" system constituted by the single pillar (which has no interactions with the rest of the structure, as in a frame structure) behaving like a cantilever.
The following "chain" of vulnerabilities is determined:

- **Roof**: loss of support of secondary element or main beams
- **Beam-column node**: low reinforcement percentage (bars and stirrups), no reliable transmittal of horizontal forces
- **Pillars**: reinforcement bars and stirrups dimensioned according to lower bound Code limits (0.3% longitudinal percentage, stirrups of small diameter with excessive pitch). Reduced element ductility at ULS and insufficient resistance.
- **Infills**: out of plane overturning
- **Column-plinth node**: pillar inserted in the prefabricated plinth (low reinforcement, does not guarantee adequate resistant moment and shear transfert at the base)
- **Plinth (foundation beam)**: foundation dimensioned only for gravity loads, possible sliding, overturning...
Weak points-connexions
Structural damages in the recent Emilia earthquake (20-29 May 2012)

Epicenters distribution
Structural damages in the recent Emilia earthquake (20-29 May 2012)

Time evolution of the earthquake sequence
Connections in prefabricated buildings

Chemical factory, Paganica (AQ)
Connections in prefabricated buildings

Industrial buildings

Out-of-plane damage of upper panels
Connections in prefabricated buildings

Industrial buildings in Emilia, 2012
Damage to fork connection due to pounding of main transverse beam

Industrial buildings in Emilia, 2012
Loss of bearing area for shed roof structures
LOSS OF SUPPORT

Industrial buildings in Emilia, 2012
Construction details & materials in prefabricated buildings

Inadequate reinforcement and concrete quality

Industrial buildings in Emilia, 2012
Damage to secondary elements

Shelf damage
(and industrial mezzanine)

Industrial buildings in Emilia, 2012
Settlements caused by soil liquefaction - Kocaeli Earthquake 1999
Thanks for your attention!

claudio.modena@dicea.unipd.it

claudio.modena@smingegneria.it

www.smingegneria.it