Seismic design of buildings
Analysis and design of earthquake resistant buildings

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Overview

1. Elements of dynamics
2. Standards Design Rules
3. Capacity design
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Non Linear SDOF System

In the previous lecture an elastic behaviour of the structure was assumed in order to study its dynamic behaviour under seismic loads. **Is this hypothesis realistic?** Can we really design earthquake resistant structure without damages?

An earthquake is a rare natural phenomenon that produces exceptional (very high) loads on the structures. Designing structures that behave in the elastic range might be **too expensive**.

**We can accept that some damages occur** taking into account the non linear behavior of a structure, that in most of cases can be represented by an elasto-plastic model, characterized by:

\[
\begin{align*}
F_y &= \text{Strength} \\
F &= \text{Strength} \\
\mu &= \frac{\Delta u}{u_0} = \text{Ductility}
\end{align*}
\]
Anelastic SDOF System

The equation of motion has a similar formulation; the only difference is that now the internal force is not linear dependent by the relative displacement.

\[ M \ddot{u}(t) + c \dot{u}(t) + ku(t) = -M\ddot{x}_0(t) \]

The solution can not be obtained in the same way of a linear SDOF system. A numerical integration in time domain (**Time history analysis**) have to be done, even if it can be very time consuming in case of many degree of freedom systems. Some past studies have demonstrated that the maximum displacement of a non linear SDOF system is very similar to the corresponding linear system one (**Newmark Hypothesis**).
Design Response Spectrum

From Newmark’s hypothesis:

\[ u_{e,\text{max}} = u_{a,\text{max}} = \mu \cdot u_y \]

For the elastic system the maximum force can be calculated as:

\[ F_{s,e,\text{max}} = m \cdot S_{A,e} \]

From the picture it is easy to realize that:

\[ \frac{F_{s,e,\text{max}}}{F_{s,y}} = \frac{u_{\text{max}}}{u_y} = \mu \]

The maximum force for the anelastic system can be calculated as:

\[ F_{s,y} = \frac{F_{s,e,\text{max}}}{\mu} = m \cdot \frac{S_{A,e}}{\mu} = S_{D,e} \]

The design force can be evaluated reducing the elastic force by the ductility!

We can define a reduced response spectrum defined as design response spectrum.
Elements of dynamics

**Design Response Spectrum**

\[ F_{s,y} = \frac{F_{s,e,max}}{\mu} = m \cdot \frac{S_{A,e}}{\mu} = S_{D,e} \]

The analysis of a non linear structure can be performed assuming an elastic behaviour and reducing the forces by the factor \( q \)!!!

The higher the ductility, the lower the design force!!!

If we design a ductile structure we can reduce the elastic force by a coefficient called factor \( q \), that is equal to the ductility. This means to reduce the elastic spectrum by the factor \( q \).

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Role of ductility in seismic response

\[ S_d(T) = S_e(T)/q \]

- The ductility properties of the structure reduces the level of the action.
- The q-factor represents the ductility level of the structures.
Energetic Approach

What’s the physical meaning of q-factor? Why can we reduce the elastic forces?

From the integration of the equation of motion it can be obtained:

\[ E_k(t) + E_{vd}(t) + E_h(t) = E_{in}(t) + E_s(t) \]

\( E_k = \) Kinetic Energy; \( E_{vd} = \) Energy Dissipated via Viscous Damping; \( E_h = \) Hysteretic Energy; \( E_{in} = \) Input Energy; \( E_s = \) Recoverable Elastic Energy;

The input energy expressed in the energy formulation is the true total energy input to the system. If we want to reduce the energy absorbed by the structure, caused by the elastic strain energy we need to increase the hysteretic energy, equal to the amount of the dissipated energy. We can reduce the elastic force if the structure can dissipate the input energy, by means of its hysteretic behaviour. However this implies damages to the structure.

\[ q \Rightarrow \text{ductility} \Rightarrow \text{dissipated energy} \]
What’s the value of q-factor?

Standards give the q-factor for a lot of different structural type and for different materials. The designer can choose between a high level of ductility (CDH) or a medium level (CDM). In the first case q-factor is higher.

In order to ensure the selected ductility level, a lot of design rules are explained according to the capacity design approach. Construction details are becoming increasingly important!!!
### Structural types for timber structures

<table>
<thead>
<tr>
<th>Structural Type</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Cross Laminated Timber (X-Lam) system</strong>, i.e. buildings comprised of X-Lam shear walls according to XX (reference to the Material Properties section) with the specifications given in YY (reference to the Capacity Design Rules section).</td>
<td><img src="image1" alt="Example" /></td>
</tr>
<tr>
<td><strong>2. Light wood-frame system</strong>, i.e. structures in which shear walls are made of timber frames to which a wood-based panel or other type of sheathing material according to XX (reference to the Material Properties section) are connected according to the specifications given in YY (reference to the Capacity Design Rules section).</td>
<td><img src="image2" alt="Example" /></td>
</tr>
<tr>
<td><strong>3. Log House building system</strong>, i.e. structures in which walls are made by the superposition of rectangular or round solid or glulam timber elements, prefabricated with carpentry joints at their ends and with upper and lower grooves according to specifications given in YY (reference to the Capacity Design Rules section).</td>
<td><img src="image3" alt="Example" /></td>
</tr>
</tbody>
</table>
### Q-factors for timber structures [Proposal]

<table>
<thead>
<tr>
<th>Structural type</th>
<th>DCM</th>
<th>DCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Lam buildings</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Light-Frame buildings</td>
<td>2,5</td>
<td>4</td>
</tr>
<tr>
<td>Log House buildings</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Moment resisting frames</td>
<td>2,5</td>
<td>4</td>
</tr>
<tr>
<td>Post and beam timber buildings</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Mixed structures made of timber framing and masonry infill resisting to the horizontal forces</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Large span arches with two or three hinged joints</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Large span trusses with nailed, screwed, doweled and bolted joints</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vertical cantilever systems made with glulam or X-Lam wall elements</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

For structures designed in accordance with the concept of low-dissipative structural behaviour (DCL) the behaviour factor q should not be taken greater than 1,5.
Traditional Design Approach

As seen previously the non linear behavior of a structure can be represented by an elasto-plastic model, characterized by strength, stiffness and ductility. *Which one is the most important?*

It depends on the intensity of the expected ground motion. For **low earthquakes** the structure should be **strength and stiff** in order to avoid damages. For **high earthquakes** the structure should be **ductile** to dissipate energy and to avoid the collapse. A very strength and ductile structure would be best but in most of cases it would be **too expensive**.

How can we design a ductile structure?

If to increase the strength of a structure may be easy (even if expensive), to increase the ductility the failure mode must be selected. In fact we have to avoid a brittle failure mode in order to assure a ductile one. In other words it is decided which elements of a structural system will be permitted to yield (ductile components) and which one are to remain elastic (brittle components). This strategy is called:

**Capacity Design**
Capacity Design

To explain the capacity design approach we can consider a chain made of glass rings and hence brittle, and one ring is made of steel and hence ductile. Suppose the chain is tauted by a force $P$.

If the strength of the steel ring is lower than the glass ring one, the behaviour of chain will be ductile. In fact the steel ring is able to stretch a lot before breaking. If the strength of the steel ring is higher than the glass ring one, the behaviour of chain will be brittle. In fact the glass ring breaks immediately after reaching its strength force.
In order to get a ductile chain the glass ring needs to be more resistant than the steel one. Hence the design force for the steel ring will be equal to $P$, but for the glass ring, that has to be in the elastic range, the design force will be equal to the resistance of the steel ring, amplified by an opportune safety factor: the overstrength factor $\gamma_{Rd}$.

$$R_{d,\text{steel}} = P$$

$$R_{d,\text{glass}} = \gamma_{Rd} \cdot R_{d,\text{steel}} \quad \gamma_{Rd} > 1$$
Capacity Design

Also a structure can be viewed as a chain where some elements are characterized by a brittle failure model some others by a ductile model one. Hence we have to avoid that brittle failure happens before yielding of ductile elements.

The designer must choose the right structure failure mode.

Ductile elements will be designed for the analysis internal forces (bending moment, shear,...). The design force for brittle elements are obtained by the equilibrium of internal forces after yielding of ductile elements.

**Shear Mechanism:** *ductile behaviour*
- Larger spacing between nails
- Strong Hold-down
  \[ R_{d,HD} \geq \gamma_{Rd} \cdot R_{d,nails} \]

**Rocking Mechanism:** *brittle behaviour*
- Smaller spacing between nails
- Weak Hold-down
  \[ R_{d,HD} \leq \gamma_{Rd} \cdot R_{d,nails} \]
The overstrength factor

The overstrength factor is used to ensure that the resistance of the brittle element is always greater than the ductile one, in order to achieve a global ductile failure of the structure.

\[ R_{\text{brittle}} \geq \gamma_{Rd} \cdot R_{\text{ductile}} \]
Another important topic to ensure a good seismic behavior of structure is their regularity. This should be taken into account in the early stages of the conceptual design of a building.

The guiding principles which should be satisfied are:

- **Structural simplicity**, characterized by the existence of clear and direct path for the transmission of the seismic forces, so that the modeling, studying and designing are subject to much less uncertainty and the structure seismic behavior is much more reliable.

- **Uniformity**, characterized by an even distribution of the structural elements which allow short and direct transmission of the inertia forces created in the distributed masses of the building. If necessary the building needs to be subdivided by seismic joint into dynamically independent units.
• Bi-directional resistance and stiffness: Horizontal seismic motion is a bi-directional phenomenon and thus the building structure shall be able to resist horizontal actions in any directions.

• Torsional resistance and stiffness: The structure should possess adequate torsional resistance and stiffness in order to limit the torsional motions which tend to stress the different structural elements in a non-uniform way.

• Diaphragmatic behavior at storey level: Floors should act as horizontal diaphragms that collect and transmit the inertia forces to the vertical structural systems and ensure that those systems act together in resisting the horizontal seismic action.
Regularity

In relation to the previous principles building structures are categorised into being **regular and non regular structures**. The second ones should be avoid and standards increase the design seismic action for this type of structures. A structure can be regular or not in elevation or in plan.
Seismic Analysis of Buildings

Another reason to ensure the regularity in elevation of building is the possibility to replace the modal analysis of the structure with a simplified method of analysis, called **lateral force method**. In fact for regular in elevation buildings the dynamic behaviour is well represented by just the first mode shape, neglecting the others. The structure can be modelled just as a SDOF system, which period $T_1$ can be evaluated by a simplified equation, function of building height $H$.

The seismic base shear force $F_b$ can be determined as the product of the total mass of the building and the ordinate of the design spectrum at period $T_1$.

$$T_1 = C_t \cdot H^{3/4} \quad F_b = S_d(T_1) \cdot m \cdot \lambda$$

$\lambda$: correctional factor
Seismic Analysis of Buildings

For most of regular in elevation building the first mode shape may be approximated by horizontal displacement increasing linearly along the height of the building.

The horizontal force acting on the storey $i$ can be calculated as:

$$F_i = F_b \cdot \frac{z_i \cdot m_i}{\sum z_i \cdot m_i}$$

$Z_i, Z_j$ are the heights of the masses $m_i, m_j$ above the level of application of the seismic action.
References

- Christopoulos C., Filiatrault A. – Principles of passive supplemental damping and seismic isolation, IUSS Press 2006