seismic design with EN 1998 and NA

Impulso XLAM de proHolz
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CONTENT

- damages on buildings caused by earthquakes
- seismic standards in Europe - results of a study
- requirements and boundary conditions according to EN 1998-1
- behaviour of buildings erected in Solid Timber Construction under seismic loads
- example
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Overview

Andreas Ringhofer

Madrid, Spain, 11th – 12th November 2011

Institute for Timber Engineering and Wood Technology

 damages on buildings caused by earthquakes

- Tohoku 03/2011
- Christchurch 02/2011
- L’Aquila 04/2009
Tohoku earthquake, 11th March 2011, magnitude 9.0

470 km² destroyed by a tsunami
26,000 dead or lost
accident in a nuclear power plant with incalculable consequences

Christchurch earthquake, 22nd February 2011, magnitude 6.3

MMI: IX - violent
more than 200 victims
13 billions $ damage costs
L’aquila earthquake, 6th April 2009, magnitude 5.8

EMS 98: IX - destructive
297 victims, 67,500 homeless persons
historical centre totally destroyed
damages on buildings caused by earthquakes

- two advertisements for Solid Timber Construction in CLT
  1. minimisation of damage and victims for existing buildings
  2. fast, earthquake resistant and ecological reconstruction in CLT

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  - example
seismic standards in Europe - results of a study

- Contents of the study
  - implementation of the EN 1998-1
  - size of the seismic actions in the different countries
  - simplifications depending on small loads
  - regulations of vertical seismic loads
  - combination of seismic loads with another ones
  - especial regulations for timber buildings
seismic standards in Europe - results of a study

- implementation of the EN 1998-1
seismic standards in Europe - results of a study

- size of the seismic actions in the different countries according to EN 1998-1

\[ \gamma_I \cdot a_{gR} \cdot S \]

“importance factor“ (0,8 - 1,4)

“soil factor“ (ground types A - E, S von 1,00 - 1,40)

“reference peak ground acceleration“ (depends on the seismic zone)

- Spain (NCSE-02) \[ \rho \cdot a_b \cdot S \]

<table>
<thead>
<tr>
<th>country</th>
<th>minimum [m/s²]</th>
<th>maximum [m/s²]</th>
<th>influenced area [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>0,00</td>
<td>1,98</td>
<td>20</td>
</tr>
<tr>
<td>Germany</td>
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<td>Switzerland</td>
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<td>3,14</td>
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<td>Spain</td>
<td>0,32</td>
<td>3,74</td>
<td>?</td>
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<tr>
<td>France</td>
<td>0,00</td>
<td>5,88</td>
<td>60</td>
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<td>Italy</td>
<td>0,00</td>
<td>6,40</td>
<td>92</td>
</tr>
<tr>
<td>Greece</td>
<td>1,28</td>
<td>7,06</td>
<td>100</td>
</tr>
</tbody>
</table>
seismic standards in Europe - results of a study

- conclusions
  - EN 1998-1 is not valid in every country
  - differences between the standards in almost every point
  - homogenisation (validation of the EN 1998-1, zones, and so more) would be preferable

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requirements and boundary conditions according to EN 1998-1

- basic principles of conceptual design
  - structural simplicity
  - uniformly, symmetry and redundancy
  - bi-directional resistance and stiffness
  - torsional resistance and stiffness
  - diaphragmatic behaviour at storey level
  - adequate foundation

requirements and boundary conditions according to EN 1998-1

structural simplicity

- existence of clear and direct paths for the transmission of the seismic forces in the building
uniformity, symmetry and redundancy

- criteria for regularity in plan
- criteria for regularity in elevation

→ have a significant effect on the seismic loadings!

criteria for regularity in plan

- the plan configuration shall be compact

setback to large!

floor in-plan stiffness is affected!
criteria for regularity in plan

- difference between the floor in-plan stiffness and the lateral stiffness of the vertical structural elements
  \[ \text{floor in-plan stiffness} >> \text{lateral stiffness of the walls (e.g.)} \]
- limitation of the slenderness \( \lambda \)

\[ \lambda = \frac{L_{\text{max}}}{L_{\text{min}}} = \frac{1400}{300} = 4.7 > 4 \]

- limitations of the structural eccentricity and the torsional radius
  \[ \text{structural eccentricity} = \text{distance between the centre of mass and the centre of lateral stiffness} \]
criteria for regularity in plan

- limitations of the structural eccentricity and the torsional radius

→ torsional radius \( r > \) radius of gyration \( l_s \)

\[
\sum (k_{y,i} \cdot x_{s,i}^2) + \sum (k_{x,i} \cdot y_{s,i}^2) \geq \frac{l_{pm}}{\sqrt{m}}
\]

criteria for regularity in elevation

- lateral load resisting systems should have no interruptions from their foundations to the top of the building

- avoiding of differences of the lateral stiffness and mass of the individual storeys

soft-storey at ground level!
criteria for regularity in elevation

- additional conditions for setbacks in elevation
  - symmetric setback
  - asymmetric setback
  - depending on the height

\[
\frac{L_2 - L_1}{L_1} \leq 0.20 \\
\frac{L_1 - L_2}{L_1} \leq 0.10 \\
\frac{L - L_2}{L} \leq 0.30 \\
\frac{L_2 + L_1}{L} \leq 0.20 \\
\frac{L_3 + L_1}{L} \leq 0.50
\]

consequences of the criteria of regularity

<table>
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<tr>
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<tbody>
<tr>
<td>plan</td>
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* calculation with the lateral force method of analysis
** calculation with the modal response spectrum analysis
bi-directional resistance and stiffness

\[ E_1 << \]

requirements and boundary conditions according to EN 1998-1

torsional resistance and stiffness

bad choice

good choice
**diaphragmatic behaviour at storey level**

- has to be proofed
- force-fitting and effective wall-ceiling-connections
- conditions for the situation of openings

**adequate foundation**

- rigid and homogeneous foundation slabs favoured
- tie-beams, piles see EC 7
the behaviour factor $q$

- EN 1998: $q$-factor as a quotient in the calculation

Example: ground type A, $a_g = 3.34 \text{ m/s}^2$

- Size depends on the ductility of the structure
- Aim: transformation of energy with large deformations
- Includes the non-linear behaviour in the linear analysis
- Is determined by tests (original scale)
The behaviour factor $q$

- seismic performance = bearing resistance x ductility

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behaviour of buildings erected in Solid Timber Construction under seismic loads

- the material
  - ceilings in CLT enable diaphragmatic behaviour
  - walls in CLT have high bearing capacities under lateral loadings
  - low mass (timber : concrete = 0,15 : 1,00)
  - high bearing capacity with small deformation
    → “low energy dissipation”

- the structural behaviour

- determining the q-factor
behaviour of buildings erected in Solid Timber Construction under seismic loads

- the structural behaviour
  - walls and ceilings in CLT as “primary seismic elements”
  - ceilings have to divide the forces up to the walls
  - walls have to transfer the forces into the foundation (M + N + V)
  - connecting the elements with anchors and brackets

  → large deformations caused by plastic hinges

  → dissipative areas of the construction

behaviour of buildings erected in Solid Timber Construction under seismic loads

- determining the q-factor
  - research topic of the Institute for Timber Engineering and Wood Technology, TU Graz, AUT
  - determining the behaviour of connections under cyclic loadings
    → actually running

  - doing wall tests with the results of step 1
    → aim for 2012

  - shaking table test of a building (original scale)
behaviour of buildings erected in Solid Timber Construction under seismic loads

- determining the q-factor
  - current state of research
    - first shaking table tests in Italy and Japan (SOFIE projekt)
    - Video
    - q-factor can be estimated to 2,0 - 3,0

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example

- contents
  - the building
  - determining the seismic parameters
  - calculation of the seismic loadings and seismic design
  - results and summary

example

- contents
  - the building
    - 5-storey residential building erected in Solid Timber Construction
    - length x width = 19.5 x 15.0 m
    - location: L’Aquila (Italy)
    - design with EN 1998-1 and the national annex of Austria
visualisation

floor plan

→ 11 walls as "primary seismic elements"

→ ceiling models as single-, two- and three-span-beams
### Cross-section

From pre-design:
- Walls: 5 layers, 95/121 mm
- Ceilings: 5 layers, 196 mm

### Determining the Seismic Parameters

\[ E_d = E_d(S, \gamma, a_g, a, m, k_i, f_{i,d,i}) \]

- Behaviour
- Stiffness
- Soil
- Mass
- Ground acceleration
- Strength

**Example**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
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<tbody>
<tr>
<td>1: OBERGESCHoss</td>
<td>15.6 m</td>
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<td>2: OBERGESCHoss</td>
<td>3.0 m</td>
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<td>3: OBERGESCHoss</td>
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<td></td>
</tr>
<tr>
<td>9: OBERGESCHoss</td>
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determining the seismic parameters

- location of the building
  - soil-factor und ground acceleration
  - soil: ground type A $\rightarrow$ S = 1.0
  - acceleration: $a_{gr} = 3.34$ m/s²

- importance of the building
  - residential or office building
  - $\gamma_I = 1.0$

- material parameters „stiffness“ und „strength“
  - stiffness: elastic and shear modulus of the particular materials
  - strength according to EC 5 resp. EC 8

- calculation of the active seismic masses
  - according to EN 1998: $\sum G_k + \sum \psi_k \cdot Q_k$

  - active seismic mass is about 660 t
    (building in reinforced concrete about 1700t)
verification of the regularity

- regularity in plan
  - is the plan configuration compact?

- regularity in elevation
  - lateral load resisting systems should have no interruptions form their foundations to the top of the building
  - avoiding of differences of the lateral stiffness and mass of the individual storeys
  - setbacks

→ elevation is regular!
### Selection of the Method of Analysis

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<td>Yes</td>
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<td>No</td>
<td>Plan Modal Decreased Value</td>
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<tr>
<td>No</td>
<td>Yes</td>
<td>Spatial Lateral Force Reference Value</td>
</tr>
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selection of the method of analysis

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- in this case:
  - calculation of the first periods with a spatial model (RFEM)
  - static forces, design „by hand“

seismic design with lateral force method of analysis

- step by step
  1. creation of the 3D-model and calculation of the first periods
  2. determination of the seismic base shear forces
  3. calculation of the internal forces
  4. design of the structural elements and capacity design

- problem
  - number of anchors, brackets and nails in step 1 unknown
  - form, number and position have a big influence to the lateral stiffness and to the seismic loads

→ iterative calculation is necessary
step 1: calculation of the first periods with an estimated number of connectors

step 2: calculation of the seismic base shear forces

step 3: calculation of the internal forces in the walls and connections

design of the connections

no

yes

capacity design

no

yes

2. iteration: increasing of the connections in high stressed walls

modification of the whole system

creation of the 3D-model with „RFEM“

- plates:
  - intermediate ceilings and top ceiling
  - modelling with a 2D-element (orthogonal-anisotropic stiffness matrix)

- members:
  - bearing walls as primary seismic elements
  - modelling with an 1D-element
    - geometrical parameters: length, with and height
    - material parameters: elastic and shear modulus

- connections/joints:
  - wall-ground plate und wall-ceiling-wall
  - modelling with springs (shear and rotation)
creation of the 3D-model with „RFEM“

- selection of the connectors
  - anchors
    - HD 480-M20
  - angle brackets
    - wall-ground plate
    - AE116
    - wall-ceiling
    - ABR90

- position of the connectors
  - brackets
  - anchors
  - both sides
creation of the 3D-model with „RFEM“

- shear stiffness of a connection/wall
  \[ k_{ser,ges} = n \cdot k_{ser,bracket} \]
  - stiffness modulus of one bracket
  - number of brackets

- rotation stiffness of a connection/wall
  \[ k_{r,ges} = \frac{z_1^2}{1} + \frac{1}{k_{compression}} \]
  - vertical force has to be known

first periods of the 1.iteration

- example
  - \( S_{a} = 0.67 \)
  - \( T_{1x} \)
  - \( T_{1y} \)
calculation of the seismic base shear forces

- lateral force method of analysis according to EN 1998-1:
  \[ F_b = S_a \cdot m \cdot \lambda \]
  \[ F_{h,x} = F_{h,y} = 441 \text{ kN} \]

- distribution on the floors depending on
  - the position to the basement (height)
  - the floor mass
  - is achieved by
  \[ F_i = F_b \cdot \frac{z_i \cdot m_i}{\sum z_i \cdot m_i} \]
calculation of the internal forces

- distribution on the walls with
  - combination translation and rotation
  - coordinates of the centre of lateral stiffness have to be known

\[ x_s = \frac{\sum k_{y,i} \cdot x_i}{\sum k_{y,i}} \]

- distance from the wall to the coordinate origin
- lateral stiffness of the walls
- bending + shear + connections
calculation of the internal forces

- coordinates of the centre of lateral stiffness

- distribution of the forces

\[ F_{b,x} \]

- translation
- rotation
calculation of the internal forces

- bending moment
  \[ M_{lx} = \sum F_{lx} \cdot z_i \]

- shear force
  \[ V_{lx} = \sum F_{lx} \]

- combination
  \[ \text{SRSS} \rightarrow M_i = \sqrt{M_{lx}^2 + M_{ly}^2} \]

example

step 1: calculation of the first periods with an estimated number of connectors

2. iteration: increasing of the connections in high stressed walls

step 2: calculation of the seismic base shear forces

step 3: calculation of the internal forces in the walls and connections

design of the connections

capacity design

no

yes

modification of the whole system

no

yes
design of the connections

- assessment of the bearing capacity
  - bending moment in the connection joint
    \[ M_{b,d,i} \leq M_{b,u,i} \quad \text{bearing moment, calculated with the wall-model} \]
  - shear force in the connection joint
    \[ V_{b,d,i} \leq R_{v,u,i} \quad \text{bearing shear force of all brackets} \]

→ bearing capacity of the connections is not enough (y-direction)
→ 2. step of iteration necessary!

flowchart:

1. calculation of the first periods with an estimated number of connectors
2. calculation of the seismic base shear forces
3. calculation of the internal forces in the walls and connections

2. iteration: increasing of the connections in high stressed walls

- design of the connections
  - capacity design
    - yes
      - modification of the whole system
    - no
      - step 1
      - step 2
      - step 3
      - no
2. step of iteration - summary

- actions
  - increasing the numbers of the connections step by step
- results
  - \( T_{1x} = 1.74 \, \text{s} \)
  - \( T_{1y} = 1.94 \, \text{s} \)

\[ \Rightarrow \text{bearing capacity of the connections enough} \]
capacity design

- verification of the hierarchy of the bearing capacities
  - verification of the reserve of brittle failures (walls) in comparison with ductile failures of the connections
  - connection with the maximum force is the wall-ground plate connection of wall 1y
    \[ r_{xy,d,\text{joint}} = 74.83 \, \text{kN/m} \]
    \[ r_{xy,d,\text{wall}} = 210.00 \, \text{kN/m} \]
  - verification
    \[ \eta = \frac{r_{xy,d,\text{wall}}}{r_{xy,d,\text{joint}}} = \frac{210.00}{74.83} = 2.81 > 1.20 \]

summary

- complex procedure because of the iterative steps
  - use of especial software or spreadsheet programs (MS Excel)
- first periods are proportionally high
  - stiffness of the connections has a big influence!
- high bearing capacities of elements which have brittle failure modes
  - high safety against collateral damages caused by brittle failures
- problems and aims for future
  - sophistication of the modeling and the calculation method
  - development of connections especially aligned for
    - Soli Timber Constructions in CLT
    - high loadings in extraordinary situations
THANK YOU FOR YOUR ATTENTION

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