EN 1991-1-7

Eurocode 1
Accidental Actions

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TNO Bouw / TU Delft
EN 1990 Section 2.1 Basic Requirements

(4)P A structure shall be designed and executed in such a way that it will not be damaged by events like

- explosion
- impact and
- consequences of human errors

to an extent disproportionate to the original cause

Note: Further information is given in EN 1991-1-7
EN 1990 guidance:

- reducing hazards
- low sensitive structural form
- survival of local damage
- sufficient warning at collapse
- tying members
(25) Progressive collapse is not an inevitable feature of high system-built blocks. It can be avoided by the introduction of sufficient steel reinforcement to give continuity at the joints, and the adoption of a plan-form which provides for the arrangement of the load-bearing walls in such a way that the load is carried by alternative paths if part of the structure fails (paragraphs 129 and 188).
World Trade Center
USA, 2001
Eurocode EN 1991-1-7

1. General
2. Classification
3. Design situations
4. Impact
5. Explosions

Annexes
A. Design for localised failure
B. Risk analysis
C. Dynamics
D. Explosions
3 Design strategies

ACCIDENTAL DESIGN SITUATIONS

STRATEGIES BASED ON IDENTIFIED ACCIDENTAL ACTIONS
  e.g. Explosions and Impact

DESIGN THE STRUCTURE TO HAVE SUFFICIENT ROBUSTNESS

PREVENTING OR REDUCING THE ACTION
  e.g. protection measures

DESIGN STRUCTURE TO SUSTAIN THE ACTION

ENHANCED REDUNDANCY
  e.g. alternative load paths

KEY ELEMENT DESIGNED TO SUSTAIN NOTIONAL ACCIDENTAL ACTION $A_d$

STRATEGIES BASED ON LIMITING THE EXTENT OF LOCALISED FAILURE

PRESCRIPTIVE RULES
  e.g. integrity and ductility
# 4. Impact

<table>
<thead>
<tr>
<th>Type of road</th>
<th>Vehicle type</th>
<th>$F_{dx}$ [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorway</td>
<td>Truck</td>
<td>1000</td>
</tr>
<tr>
<td>Country roads</td>
<td>Truck</td>
<td>750</td>
</tr>
<tr>
<td>Urban area</td>
<td>Truck</td>
<td>500</td>
</tr>
<tr>
<td>Parking place</td>
<td>Truck</td>
<td>150</td>
</tr>
<tr>
<td>Parking place</td>
<td>Passenger car</td>
<td>50</td>
</tr>
</tbody>
</table>
Annex B: scenario model
Annex C: force model

\[ F = v \sqrt{(km)} \]

model en experiment
Table 4.2.1: Data for probabilistic collision force calculation

<table>
<thead>
<tr>
<th>variable</th>
<th>designation</th>
<th>type</th>
<th>mean</th>
<th>stand dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>number of lorries/day</td>
<td>deterministic</td>
<td>5000</td>
<td>-</td>
</tr>
<tr>
<td>T</td>
<td>reference time</td>
<td>deterministic</td>
<td>100 years</td>
<td>-</td>
</tr>
<tr>
<td>λ</td>
<td>accident rate</td>
<td>deterministic</td>
<td>$10^{-10} \text{ m}^{-1}$</td>
<td>-</td>
</tr>
<tr>
<td>b</td>
<td>width of a vehicle</td>
<td>deterministic</td>
<td>2.50 m</td>
<td>-</td>
</tr>
<tr>
<td>α</td>
<td>angle of collision course</td>
<td>rayleigh</td>
<td>10°</td>
<td>10°</td>
</tr>
<tr>
<td>v</td>
<td>vehicle velocity</td>
<td>lognormal</td>
<td>80 km/hr</td>
<td>10 km/hr</td>
</tr>
<tr>
<td>a</td>
<td>deceleration</td>
<td>lognormal</td>
<td>$4 \text{ m}^2/\text{s}$</td>
<td>1.3 m/s$^2$</td>
</tr>
<tr>
<td>m</td>
<td>vehicle mass</td>
<td>normal</td>
<td>20 ton</td>
<td>12 ton</td>
</tr>
<tr>
<td>k</td>
<td>vehicle stiffness</td>
<td>deterministic</td>
<td>300 kN/m</td>
<td>-</td>
</tr>
</tbody>
</table>
Life time exceedence probability: $10^{-3}$
Design example: bridge column in motorway

- **b** width: 0.50 m
- **h** thickness: 1.00 m
- **H** column height: 5 m
- **f_y** yield stress steel: 300 MPa
- **f_c** concrete strength: 50 MPa
- **ρ** reinforcement ratio: 0.01
Bending moment:

\[ M_{dx} = \frac{a(H-a)}{H} F_{dx} = \frac{1.25 (5.00-1.25)}{5.00} 1000 = 940 \text{kNm} \]

Resistance:

\[ M_{Rdx} = 0.8 \omega h^2 b f_y \]

\[ = 0.8 \times 0.01 \times 1.00^2 \times 0.50 \times 300 \times 000 \]

\[ = 1200 \text{kNm} > 940 \text{kNm} \]
5 + Annex D:

gas explosions in buildings

gas explosions in tunnels

dust explosions
INTERNAL NATURAL GAS EXPLOSIONS

The design pressure is the maximum of:

\[ p_d = 3 + p_v \]
\[ p_d = 3 + 0.5 \ p_v + 0.04/(A_v/V)^2 \]

- \( p_d \) = nominal equivalent static pressure [kN/m²]
- \( A_v \) = area of venting components [m²]
- \( V \) = volume of room [m³]

Validity: \( V < 1000 \text{ m}^3 \); \( 0.05 \text{ m}^{-1} \leq A_v/V \leq 0.15 \text{ m}^{-1} \)

Annex B: load duration = 0.2 s
**Design Example: Compartment in a multi story building**

**Compartment: 3 x 8 x 14 m**

**Two glass walls** \( (p_v = 3 \text{ kN/m}^2) \) and two concrete walls
explosion pressure:

\[ p_{Ed} = 3 + p_{V/2} + 0.04/(A\sqrt{V})^2 \]
\[ = 3 + 1.5 + 0.04 / 0.144^2 = 6.5 \text{ kN/m}^2 \]

self weight = 3.0 kN/m²

live load = 2.0 kN/m²

Design load combination (bottom floor):

\[ p_{da} = p_{SW} + p_{E} + \psi_{1LL} \ p_{LL} \]
\[ = 3.00 + 6.50 + 0.5 \times 2.00 = 10.50 \text{ kN/m}^2 \]
Dynamic increase in load carrying capacity

\[
\varphi_d = 1 + \sqrt{\frac{p_{SW}}{p_{Rd}}} \cdot \sqrt{\frac{2 \cdot u_{\text{max}}}{g \cdot (\Delta t)^2}}
\]

\[
\Delta t = 0.2 \text{ s} = \text{load duration}
\]

\[
g = 10 \text{ m/s}^2
\]

\[
u_{\text{max}} = 0.20 \text{ m} = \text{midspan deflection at collapse}
\]

\[
p_{SW} = 3.0 \text{ kN/m}^2 \text{ and } p_{Rd} = 7.7 \text{ kN/m}^2
\]

\[
\varphi_d = [1 + \sqrt{\frac{3}{7.7}} \cdot \frac{2 \cdot 0.20}{10 \cdot (0.2)^2}] = 1.6
\]

\[
p_{REd} = \varphi_d p_{Rd} = 1.6 \cdot 7.7 = 12.5 \text{ kN/m}^2 > 10.5 \text{ kN/m}^2
\]

Conclusion: bottom floor system okay
Be careful for upper floors and columns
stabiliteit wordt niet ontleend aan de tunnel, maar aan naast de tunnel gelegen gebouwen

bebouwing (max 6 lagen, kan doorgaan tot naast de tunnel)

BLEVE in een overkluizing
## Annex A: Classification of buildings

<table>
<thead>
<tr>
<th>Consequences class</th>
<th>Example structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>class 1</td>
<td>low rise buildings where only few people are present</td>
</tr>
<tr>
<td>class 2, lower group</td>
<td>most buildings up to 4 stories</td>
</tr>
<tr>
<td>class 2, upper group</td>
<td>most buildings up to 15 stories</td>
</tr>
<tr>
<td>class 3</td>
<td>high rise building, grand stands etc.</td>
</tr>
</tbody>
</table>
## Annex A: What to do

<table>
<thead>
<tr>
<th>Class 1</th>
<th>No special considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 2, Lower Group Frames</td>
<td>Horizontal ties in floors</td>
</tr>
<tr>
<td>Class 2, Lower group Wall structures</td>
<td>Full cellular shapes Floor to wall anchoring.</td>
</tr>
<tr>
<td>Class 2, Upper Group</td>
<td>Horizontal ties and effective vertical ties OR limited damage on notional removal OR special design of key elements</td>
</tr>
<tr>
<td>Class 3</td>
<td>Risk analysis and/or advanced mechanical analysis recommended</td>
</tr>
</tbody>
</table>
Class 2a (lower group)

\[ s = 4 \text{ m} \quad s = 4 \text{ m} \]

\[ \text{interne trekband } T_i \]

\[ L = 5 \text{ m} \]

\[ \text{alle liggers kunnen worden ontworpen om als trekband te dienen} \]

\[ \text{omtrek trekband } T_p \]

\[ \text{interne trekband } T_i \]

\[ \text{randkolom} \]
Class 2a (lower group)

\[ T_i = 0.8 \left( g_k + \Psi q_k \right) sL = 0.8 \{3 + 0.5 \times 3 \} \times 4 \times 5 = 88 \text{ kN} > 75 \text{ kN} \]

*FeB 500:* \( A = 202 \text{ mm}^2 \) or \( 2 \Theta 12 \text{ mm} \)
Background horizontal typings

**total load on center column**

\[ R = (g_k + \psi q_k) L s = p L s \]
Background typing forces

\[ T_i = 0.75 \rho s L \]
Equilibrium for \( \delta = (s+L)/6 \)
Suggestion:

design corner column as a key element.
Example structure, Class 2, Upper Group, Framed

$L = 7.2 \text{ m}$, $s = 6 \text{ m}$, $q_k = g_k = 4 \text{ kN/m}^2$, $\Psi = 1.0$
Example structure

Internal horizontal tie force

\[ T_i = 0.8 \left( g_k + \Psi q_k \right) s L = 0.8 \{4+4\} (6 \times 7.2) = 276 \, \text{kN} \]

*FeB 500: A = 550 mm\(^2\) or 2 ø18 mm.*

Vertical tying force:

\[ T_i = (g_k + \Psi q_k) s L = \{4+4\} (6 \times 7.2) = 350 \, \text{kN} \]

*FeB 500: A = 700 mm\(^2\) or 3 ø18 mm.*
Class 2 higher class – walls

interne trekband $T_i$

omtrek trekband $T_p$

dragende wand

1.2 m
Class 2 higher class – walls

Tyings

Horizontal: \[ T_i = F_t \left( g_k + \psi q_k \right) / 7.5 \times z/5 \text{ kN/m} > F_t \]
Periphery: \[ T_p = F_t \]
Vertical: \[ T = \frac{34 A}{8000 \times (H/t)^2} \text{ in N} > 100 \text{ kN/m} \]

\[ F_t = 20 + 4n_s \text{ kN/m} < 60 \text{ kN/m} \]

\[ n_s = \text{number of storeys} \]
\[ z = \text{span} \]
\[ A = \text{horizontal cross section of wall [mm}^2\text{]} \]
\[ H = \text{free storey height} \]
\[ t = \text{wall thickness} \]
Design Example:

$L = 7,2 \text{ m}, \ H = 2,8 \text{ m en } t = 250 \text{ mm}$

$T = 34 \times 7200 \times 250/8000 \times (2800/250)^2 =$

$= 960 \times 10^3 \text{ N} = 960 \text{ kN} > 720 \text{ kN}$

maximal distance 5 m
maximal distance from edge: 2.5 m

Result: 2 tyings of 480 kN
Effect of tyings in walls
Effect of vertical tyings
class 3: Risk analysis

Guidance can be found in Annex B:

Definition of scope and limitations

Qualitative Risk analysis
- hazard identification
- hazard scenarios
- description of consequences
- definition of measures

Quantitative Risk Analysis
- inventory of uncertainties
- modelling of uncertainties
- probabilistic calculations
- quantification of consequences
- calculation of risks

Risk management
- risk acceptance criteria
- decision on measures

Presentation

Reconsideration of scope and assumptions
Risk Analysis
Eastern Scheldt
Storm Surge Barrier (1980)
Office building Zwolle (The Netherlands)

London Eye
Points of attention in risk analysis

- list of hazards
- irregular structural shapes new
- construction types or materials
- number of potential casualties
- strategic role (lifelines)
### Hazards

<table>
<thead>
<tr>
<th>Natural Disasters</th>
<th>Man-Made Hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake</td>
<td>Vandalism</td>
</tr>
<tr>
<td>Landslide</td>
<td>Demonstrations</td>
</tr>
<tr>
<td>Tornado</td>
<td>Terrorist attack</td>
</tr>
<tr>
<td>Avalanche</td>
<td></td>
</tr>
<tr>
<td>Rock fall</td>
<td>Design error</td>
</tr>
<tr>
<td>High groundwater</td>
<td>Material error</td>
</tr>
<tr>
<td>Flood</td>
<td>Construction error</td>
</tr>
<tr>
<td>Volcano eruption</td>
<td>User error</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engineered Hazards</th>
<th>Environmental Hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal explosion</td>
<td>Environmental attack</td>
</tr>
<tr>
<td>External explosion</td>
<td></td>
</tr>
<tr>
<td>Internal fire</td>
<td></td>
</tr>
<tr>
<td>External fire</td>
<td></td>
</tr>
<tr>
<td>Impact by vehicle</td>
<td></td>
</tr>
<tr>
<td>etc</td>
<td></td>
</tr>
<tr>
<td>Mining subsidence</td>
<td></td>
</tr>
<tr>
<td>Environmental</td>
<td></td>
</tr>
<tr>
<td>attack</td>
<td></td>
</tr>
</tbody>
</table>
Step 1
Identifical and modelling of relevant accidental hazards

Step 2
Assessment of damage states to structure from different hazards

Step 3
Assessment of the performance of the damaged structure

Assessment of the probability of occurrence of different hazards with different intensities

Assessment of the probability of different states of damage and corresponding consequences for given hazards

Assessment of the probability of inadequate performance(s) of the damaged structure together with the corresponding consequence(s)
Risk calculation:

Step 1: identification of hazard $H_i$

Step 2: damage $D_j$ at given hazard

Step 3: structural behaviour $S_k$ and cpmsequences $C(S_k)$

\[
Risk = p(H_i)p(D_j|H_i)p(S_k|D_j)C(S_k)
\]

Take sum over all hazards and damage types
Conclusions

EN 1991-1-7: valuable document,
but not a masterpiece of European harmonisation

Reasons:
- large prior differences
- member state autonomy in safety matters
- legal status different in every country

It will be interesting to see the National Annexes and NDP’s.
Relevant Background Documents

ISO-documents

COST actions C28 and TU0601

Background document for the ENV-version of EC1 Part 2-7 (TNO, The Netherlands, 1999)

Leonardo da Vinci Project CZ/02/B/F/PP-134007
Handbooks Implementtion of Eurocodes (2005)