DESIGN OF WATER RETAINING STRUCTURES TO EUROCODES

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Design of Water Retaining Structures

- Introduction
- Eurocodes
- Actions on structures and partial factors
- Durability
- Ultimate Limit State Design
- Serviceability Limit State
- Crack control
  - Flexural Cracking
  - Thermal Cracking
- Geotechnical Design
- Detailing Rules

What is a Water Retaining Structure?

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What is a Liquid Retaining Structure?

What is a Water Retaining Structure?

- The code of practice uses the term "*liquid*"
- The code of practice defines "*tank*" as a "*containment structure used to store liquids*"
- The design rules for tanks apply only to tanks storing liquids at normal atmospheric pressure

EN 1992-3 Liquid retaining and containment structures

- Additional rules for structures constructed from concrete for containment of liquid and granular solids
- This is to be read in conjunction with EN1992-1-1.
- This does NOT cover
  - Storage of material at very low or very high temperatures
  - Storage of hazardous materials where leakage could constitute a major health or safety risk
  - The selection and design of liners or coatings
  - Pressurised vessels
  - Floating structures
  - Large Dams
  - Gas tightness

Eurocodes

- Eurocode 0, *Basis of Design*
- Eurocode 1, *Actions on structures*
  - EN 1991-1-5, *Part 1-5: General Actions – Thermal actions*
  - EN 1991-4, *Part 4: Silos and Tanks*
- Eurocode 2, *Design of Concrete Structures*
  - EN 1992-1-1, *Part 1-1: General rules and rules for buildings*
  - EN 1992-3, *Part 3: Liquid Retaining and Containment Structures*
- Eurocode 7, *Geotechnical Design of Concrete Structures*
  - EN 1997-1,*Part 1: General rules*

- Eurocode 3, *Design of Steel Structures*
  - EN 1993-4-2, *Part 4.2: Steel Tanks*

Eurocode 2/BS8110 Compared

- Code deals with phenomenon, rather than element types
- Design is based on characteristic cylinder strength
- Does not contain derived formulae (e.g. only the details of the stress block is given, not the flexural design formulae)
- Units of stress in MPa
- One thousandth is represented by ‰
- Plain or mild steel not covered
- Notional horizontal loads considered in addition to lateral loads
- Higher strength, up to C90/105 covered.

Action on Structures

From EN1991-4

- Section 2 - *Representation and classification of actions*
  - Liquids shall be represented by a hydrostatic distributed load
  - Variable Fixed action
- Section 3 - *Design Situation*
  - Loads shall be considered both when tank is in operation and full
  - If levels are different then the “Full” shall be considered an accidental action
- Section 7 - *Loading on tanks due to liquid*
  - The characteristic value of pressure p should be determined as:

$$p(z) = \gamma z \qquad \dots (7.1)$$

where:

z is the depth below the liquid surface;

γ is the unit weight of the liquid.

EN 1990: Classification of Actions

- **Variation in time:**
  - *Permanent (ie Dead Load)*
  - *Variable (ie Live Load)*
  - *Accidental (ie Impact Load)*
- **Origin:**
  - *Direct (ie Dead or Live Load)*
  - *Indirect (ie Shrinkage, settlement)*
- **Spatial Variation:**
  - *Fixed (ie Dead Load)*
  - *Free (ie Live Load, Vehicle)*
- **Nature and/or structural response:**
  - *Static (ie Dead and Live Load)*
  - *Dynamic (ie Vibration from Pumps)*

Action on Structures

From EN1991-4

- **Annex B - *Actions, partial factors and combinations of actions on tanks***
  - Liquid induced loads γ_F = 1,20 for operational γ_F = 1,0 for testing
  - Internal pressure loads See EN 1990
  - Thermally induced loads See EN 1990
  - Self weight loads See EN 1990
  - Insulation loads See EN 1990
  - Distributed imposed load See EN 1990
  - Concentrated imposed load See EN 1990
  - Snow See EN 1990
  - Wind See EN 1990
  - Suction due to inadequate venting See EN 1990
  - Seismic loadings See EN 1990
  - Loads resulting from connections See EN 1990
  - Loads resulting from uneven settlement See EN 1990
  - Accidental actions γ_F = 1,0

Action on Structures

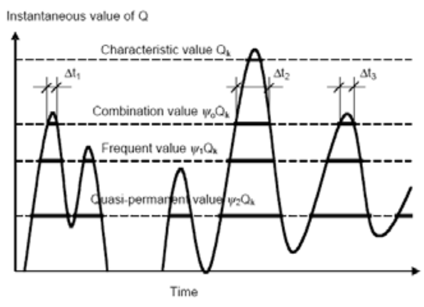
From EN1991-4

- **Annex B - *Actions, partial factors and combinations of actions on tanks***
- Combination of actions
  - The general requirements of EN 1990, Section 6 shall be followed.
  - Imposed loads and snow loads need not be considered to act simultaneously.
  - Seismic actions need not be considered to act during test conditions.
  - Accidental actions need not be considered to act during test conditions, but that the combination rules for accidental actions given in EN 1990 are applied.

EN 1990: Basis of Design

- Actions (*F*)
  - Permanent Actions (*G*)
  - Variable Actions (*Q*)
  - Accidental Actions (*A*)
  - Seismic Action (A_e)
- Values of Actions
  - Representative Values of Actions
    - Characteristic Value (Q_k)
    - Combinations Value of a Variable Action ($\psi_0 Q_k$)
    - Frequent Value of a Variable Action ($\psi_1 Q_k$)
    - Quasi-permanent Value of a Variable Action ($\psi_2 Q_k$)

(ψ) = Reduction Coefficients for Variable Actions Q_k



Combinations for Ultimate Limit State for *persistent or transient design*

$$\sum_{j\geq1} \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} \qquad (6.10)$$

or, alternatively for STR and GEO limit states, the less favourable of the two following expressions:

$$\begin{cases} \sum_{j\geq1} \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} \psi_{0,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} & (6.10a) \\ \sum_{j\geq1} \xi_j \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} & (6.10b) \end{cases}$$

As ψ_0 is not defined for water assume = 1,0

Use 6.10

Combinations for Ultimate Limit State for *accidental design situations*

$$\sum_{j\geq1} G_{k,j} \text{"+"} P \text{"+"} A_d \text{"+"} (\psi_{1,1} \text{ or } \psi_{2,1}) Q_{k,1} \text{"+"} \sum_{i>1} \psi_{2,i} Q_{k,i} \qquad (6.11b)$$

Note: EN1991-4 has given γ_f=1,0 thus A_d=1,0xAccidental action

ψ_1 is not defined for water assume = 1,0

Combinations for Serviceability Limit State for *persistent or transient design*

Frequent Actions

$$\sum_{j\geq1} G_{k,j} \text{"+"} P \text{"+"} \psi_{1,1}Q_{k,1} \text{"+"} \sum_{i>1}\psi_{2,i}Q_{k,i} \qquad (6.15b)$$

As ψ_1 is not defined for water assume = 1,0

Quasi-permanent Actions

$$\sum_{j\geq1} G_{k,j} \text{"+"} P \text{"+"} \sum_{i\geq1}\psi_{2,i}Q_{k,i} \qquad (6.16b)$$

As ψ_2 is not defined for water assume = 1,0

Example

Persistent/transient & Quasi-permanent

Q_{water} = 10kN/m³ x 5m per m
= 50kN/m² per m

Accidental

Q_{water} = 10kN/m³ x 6m per m
= 60kN/m² per m

ULS – Persistent/transient

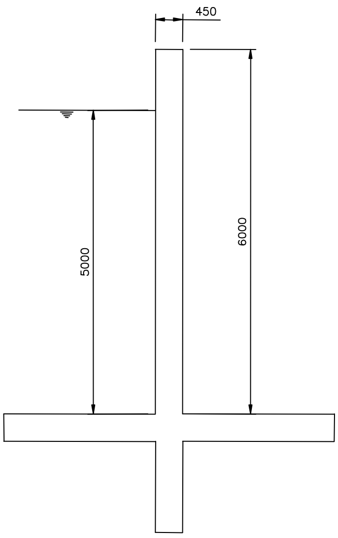
Total Action = 1,2x50=60kN/m² per m

ULS - Accidental

Total Action = 1,0x60=60kN/m² per m

SLS - Quasi-permanent

Total Action = 1,0x50=50kN/m² per m



Example

ULS – Persistent/transient

BM = $60 \times 5^2/6$ = 250kNm per m

SF = $60 \times 5/2$ = 150kN per m

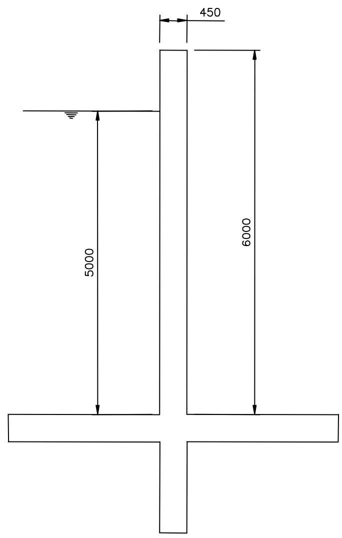
ULS - Accidental

BM = $60 \times 6^2/6$ = 360kNm per m

SF = $60 \times 6/2$ = 180kN per m

SLS - Quasi-permanent

BM = $50 \times 5^2/6$ = 208kNm per m



EN 1992-3 Liquid retaining and containment structures

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- This is to be read in conjunction with EN1992-1-1.
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  - Storage of material at very low or very high temperatures
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  - The selection and design of liners or coatings
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  - Floating structures
  - Large Dams
  - Gas tightness

Durability and cover to reinforcement

- Nominal Cover
  - $c_{nom} = c_{min} + \Delta c_{dev}$

    where

    c_{min} should be set to satisfy the following:
    - Safe transmission of bond forces (ie > bar size)
    - Durability

    Δc_{dev} is 10mm unless fabrication is QA then use 5mm

Durability and cover to reinforcement

Table NA.2 — Recommendations for normal-weight concrete quality for exposure classes XC, XD and XS and cover to reinforcement for a 50 year intended working life and 20 mm maximum aggregate size

Exposure conditions[a]			Cement/ combination types[b]	Nominal cover ($c_{min} + \Delta c_{dev}$)[c] to reinforcement (including prestressing steel) in mm and associated recommended designed concrete and equivalent designated concrete[d]							
				$15 + \Delta c_{dev}$	$20 + \Delta c_{dev}$	$25 + \Delta c_{dev}$	$30 + \Delta c_{dev}$	$35 + \Delta c_{dev}$	$40 + \Delta c_{dev}$	$45 + \Delta c_{dev}$	$50 + \Delta c_{dev}$
Carbonation induced corrosion	XC1	Dry or permanently wet	All	C20/25, 0,7, 240 or RC25	⇦	⇦	⇦	⇦	⇦	⇦	⇦
	XC2	Wet, rarely dry	All	—	—	C25/30, 0,65, 260 or RC30	⇦	⇦	⇦	⇦	⇦
	XC3	Moderate humidity	All except IVB	—	C40/50, 0,45, 340 or RC50	C32/40, 0,55, 300 or RC40	C28/35, 0,60, 280 or RC35	C25/30, 0,65, 260 or RC30	⇦	⇦	⇦
	XC4	Cyclic wet and dry									
Chloride induced corrosion excluding chlorides from seawater	XD1	Moderate humidity	All	—	—	C40/50, 0,45, 360	C32/40, 0,55, 320	C28/35, 0,60, 300	⇦	⇦	⇦
	XD2	Wet, rarely dry	I, IIA, IIB-S, SRPC	—	—	—	C40/50, 0,40, 380	C32/40, 0,50, 340	C28/35, 0,55, 320	⇦	⇦
			IIB-V, IIIA	—	—	—	C35/45, 0,40, 380	C28/35, 0,50, 340	C25/30, 0,55, 320	⇦	⇦
			IIIB, IVB	—	—	—	C32/40, 0,40, 380	C25/30, 0,50, 340	C20/25, 0,55, 320	⇦	⇦
	XD3	Cyclic wet and dry	I, IIA, IIB-S, SRPC	—	—	—	—	—	C45/55, 0,35, 380	C40/50, 0,40, 380	C35/45, 0,45, 360
			IIB-V, IIIA	—	—	—	—	—	C35/45, 0,40, 380	C32/40, 0,45, 360	C28/35, 0,50, 340
			IIIB, IVB	—	—	—	—	—	C32/40, 0,40, 380	C28/35, 0,45, 360	C25/30, 0,50, 340

NOTE 1 ⇦ indicates that the concrete given in the cell to the left applies.
NOTE 2 Reference should be made to BS 8500-1:2002, Annex A for selecting the quality of concrete subjected to freeze/thaw conditions and concrete in aggressive ground conditions.

[a] Exposure conditions conform to BS EN 206-1:2000.
[b] Cement/combination types are defined in BS 8500-2:2002, Table 1.
[c] For values of Δc_{dev}, see BS EN 1992-1-1:2003, 4.4.1.3 (1) and (3).
[d] The recommended designed concrete is taken from BS 8500-1:2002 and described in this table in terms of strength class, maximum w/c ratio, minimum cement or combination content in kg/m^3. The equivalent recommended designated concrete is taken from BS 8500-1:2002 and indicated in this table by the designation RC.

Durability and cover to reinforcement

Table NA.2 — Recommendations for normal-weight concrete quality for exposure classes XC, XD and XS and cover to reinforcement for a 50 year intended working life and 20 mm maximum aggregate size *(continued)*

Exposure conditions[a]			Cement/ combination types[b]	Nominal cover ($c_{min} + \Delta c_{dev}$)[c] to reinforcement (including prestressing steel) in mm and associated recommended designed concrete and equivalent designated concrete[d]							
				$15 + \Delta c_{dev}$	$20 + \Delta c_{dev}$	$25 + \Delta c_{dev}$	$30 + \Delta c_{dev}$	$35 + \Delta c_{dev}$	$40 + \Delta c_{dev}$	$45 + \Delta c_{dev}$	$50 + \Delta c_{dev}$
Seawater induced corrosion	XS1	Airborne salts but no direct contact	I, IIA, IIB-S, SRPC	—	—	—	C50/60, 0,35, 380	C40/50, 0,45, 360	C35/45, 0,50, 340	⇦	⇦
			IIB-V, IIIA	—	—	—	C45/55, 0,35, 380	C35/45, 0,45, 360	C32/40, 0,50, 340	⇦	⇦
			IIIB, IVB	—	—	—	C35/45, 0,40, 380	C28/35, 0,50, 340	C25/30, 0,55, 320	⇦	⇦
	XS2	Wet, rarely dry	I, IIA, IIB-S, SRPC	—	—	—	C40/50, 0,40, 380	C32/40, 0,50, 340	C28/35, 0,55, 320	⇦	⇦
			IIB-V, IIIA	—	—	—	C35/45, 0,40, 380	C28/35, 0,50, 340	C25/30, 0,55, 320	⇦	⇦
			IIIB, IVB	—	—	—	C32/40, 0,40, 380	C25/30, 0,50, 340	C20/25, 0,55, 320	⇦	⇦
	XS3	Tidal, splash and spray zones	I, IIA, IIB-S, SRPC	—	—	—	—	—	—	C45/55, 0,35, 380	C40/50, 0,40, 380
			IIB-V, IIIA	—	—	—	—	—	C35/45, 0,40, 380	C32/40, 0,45, 360	C28/35, 0,50, 340
			IIIB, IVB	—	—	—	—	—	C32/40, 0,40, 380	C28/35, 0,45, 360	C25/30, 0,50, 340

NOTE 1 ⇦ indicates that the concrete given in the cell to the left applies.
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Concrete Specification

- Minimum cement content to be 325kg/m^3
- 100% CEM I and max w/c ratio 0.55 – Not recommended
  (Max cement not to exceed 450kg/m^3)
- CEM II/V-B or CII/V-B (with <35% pfa) and max w/c ratio 0.50
  (Max cement not to exceed 450kg/m^3)
- CEM III/A or CIII/A (with <50% ggbs) and max w/c ratio 0.50
  (Max cement not to exceed 400kg/m^3)

Concrete Specification

			GGBS	PFA
1.	Concrete Reference		**GGBS**	**PFA**
2.	Compressive strength class		C28/35	C28/35
3.	Maximum aggregate size, mm		20	20
4.	Type of aggregate	Coarse Fine	BS EN 12620 BS EN 12620	BS EN 12620 BS EN 12620
5.	Design chemical class		DC 2	DC 2
6.	Cement type(s)		III/A Cement ≥ 50%	II/B-V Cement ≥ 65%
7.	Maximum Exposure class		XC4,XD1,XS1 and XF1	XC4,XD1,XS1 and XF1
8.	Minimum cement content kg/m^3		340	340
9.	Maximum free water/cement ratio		0.50	0.50

The structural performance level is normal, with an intended working life of at least 50 years.
Nominal cover is 50mm including Δc which has been taken as 10mm.

Durability – Bacterial Acid Corrosion

Durability – Low pH

Durability – Chemical attack (Aggressive CO_2)

Durability - Abrasion

Ultimate Limit State Design

Bending Moment

$$K = \frac{M}{bd^2 f_{ck}}$$

$$K' = 0{,}6\delta - 0{,}18\delta^2 - 0{,}21$$

It is often recommended in the UK that K' is limited to 0.168 to ensure ductile failure

If K>K' then not recommended thus amend section properties

$$z = \frac{d}{2}\left[1 + \sqrt{1 - 3{,}53K}\right] \leq 0{,}95d$$

$$A_s = \frac{M}{f_{yd} z} \qquad A_{s,\min} = \frac{0{,}26 f_{ctm} b_t d}{f_{yk}}$$

Ultimate Limit State Design

Shear Force

$$V_{Rd,c} = \left[\frac{0{,}18}{\gamma_c} k(100\rho_l f_{ck})^{\frac{1}{3}}\right] b_w d \qquad V_{Rd,c} = (v_{\min}) b_w d$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2{,}0 \qquad \rho_l = \frac{A_{sl}}{b_w d} \leq 0{,}02 \qquad v_{\min} = 0{,}0035 k^{\frac{3}{2}} f_{ck}^{\frac{1}{2}}$$

Example – Persistent/Transient

- f_{ck}=30N/mm² (Cylinder strength)
- Cover, c = 40mm
- Assume B20 bars
- d = 450-40-20/2=400mm
- K = 250x10⁶/(1000x400²x30) = 0,052
- K' = 0,168 > K – No compression reinforcement require
- z = 400/2x(1+√(1-3,53x0,052))=380,7mm
- 0,95x400 = 380mm > z – Use 0,95d
- A_s = 250x10⁶/(0,87x500x380) = 1512mm²

- Consider B20 at 200 (A_s=1570mm²)

Example – Accidental

- f_{ck}=30N/mm² (Cylinder strength)
- Cover, c = 40mm
- Assume B20 bars
- d = 450-40-20/2=400mm
- K = 360x10⁶/(1000x400²x30) = 0,075
- K' = 0,168 > K – No compression reinforcement require
- z = 400/2x(1+√(1-3,53x0,075))=371,5mm
- 0,95x400 = 380mm > z – Use z
- A_s = 360x10⁶/(1,0x500x371,5) = 1938mm²
- Consider B20 at 150 (A_s=2093mm²)

Example

Shear Force

- Persistent/Transient
  - ρ_l =2093/(1000x400)=0,00523 < 0,02
  - k =1+√(200/400)=1,7071 < 2,0
  - $V_{Rd,c}$ = [0,18/1,5x 1,7071 x(100x 0,00523x30)$^{0.33}$]x1000x400=203,3kN
  - V_{Ed} = 150kN < $V_{Rd,c}$
  - B20 at 150 (A_s=2093mm²) Okay
- Accidental
  - ρ_l =2093/(1000x400)=0,00523 < 0,02
  - k =1+√(200/400)=1,7071 < 2,0
  - $V_{Rd,c}$ = [0,18/1,2x 1,7071 x(100x 0,00523x30)$^{0.33}$]x1000x400=254,1kN
  - V_{Ed} = 180kN < $V_{Rd,c}$
  - B20 at 150 (A_s=2093mm²) Okay

Serviceability Limit State (SLS)

- Stress limitation
- Crack Control
- Deflection Control

SLS – Stress Limitation

- This gives the limits on compressive stress in order to avoid longitudinal cracks, micro-cracks or high levels of creep
- This limits the compressive stress to k_1f_{ck}
  where
  k_1=0,6
  and
  f_{ck}= characteristic compressive cylinder strength at 28 days
- In addition if the stress under quasi-permanent loads is less than k_2f_{ck} linear creep can be assumed
  where
  k_2=0,45
- This the requirement of EN1992-1-1 (Not EN1992-3)
- No stress checks have been undertaken for the past 50 years
- Provided the design has been carried properly to ULS – no issues expected

Crack Control

- Flexural Cracking
- Thermal Cracking incl Creep and Shrinkage Cracking

Crack Control

- Classification of tightness

Tightness Class	Requirement for leakage
0	Some degree of leakage acceptable, or leakage of liquid irrelevant
1	Leakage to be limited to a small amount. Some surface staining or damp patches acceptable
2	Leakage to be minimal. Appearance not to be impaired by staining
3	No leakage permitted

Aesthetics

Crack Control

- Appropriate limits to cracking

Tightness Class	Provision
0	Adopt provisions in 7.3.1 of EN1992-1-1
1	Crack expected to pass through whole section – use w_{k1} As Class 0 when full section is NOT cracked including min. compressive area and strain < $150x10^{-6}$
2	Crack expected to pass through whole section to be avoided unless appropriate measures (eg liner or waterbar)
3	Generally special measures will be required to watertightness (eg liner or prestress)

Crack Control

EN1992

- Class 0 w_k= 0,4 for X0,XC1 for
  w_k= 0,3 for XC2,XC3,XC4
  XD1,XD2
  XS1,XS2,XS3
- Class 1
  For $h_D/h \leq 5$, w_k= 0,2
  For $h_D/h \geq 35$, w_k= 0,05
  linear interpolation between 0,2 & 0,05
- Class 2 – No value given
- Class 3 – No value given

BS8110 & BS8007

- 0.3mm BS8110 Part 2
- 0.2mm BS8007
  for severe or very severe exposure
- 0.1mm BS8007
  for critical aesthetic appearance

Example – Class 1

EN1992

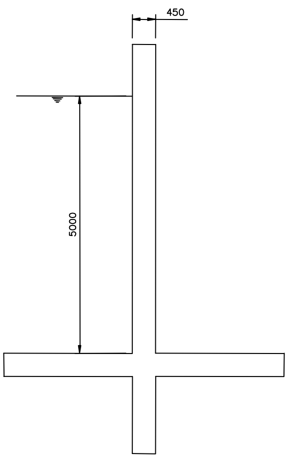
h_D = 5m depth of liquid

h = 0,45m wall thickness

- h_D/h= 11,11
- Therefore interpolate
  w_k=0,2–(11,11-5)x(0,2-0,05)/(35-5)
  = 0,169mm

BS8007

Design crack width = 0.2mm



Flexural Cracking

Tension Cracking

Calculation of crack width

- EN1992

$$w_k = s_{r,\max}(\varepsilon_{sm} - \varepsilon_{cm}) \qquad (7.8)$$

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \frac{f_{ct,eff}}{\rho_{p,eff}}\left(1 + \alpha_e \rho_{p,eff}\right)}{E_s} \geq 0{,}6\frac{\sigma_s}{E_s} \qquad (7.9)$$

$$\rho_{p,eff} = \frac{\left(A_s + \xi_1^2 A_p'\right)}{A_{c,eff}} = \frac{A_s}{A_{c,eff}} \qquad (7.10)$$

$$\alpha_e = \frac{E_s}{E_{cm}} \qquad E_{cm} = 22\left(\frac{f_{ck}+8}{10}\right)^{0.3}$$

$$s_{r,\max} = k_3 c + \frac{k_1 k_2 k_4 \phi}{\rho_{p,eff}} \qquad (7.11)$$

- c=cover, ϕ=bar size
- k_t = 0,6 short term
  = 0,4 long term

- Derived from Stress Block for bending

$$\frac{x}{d} = -\alpha_e \rho + \left[\alpha_e^2 \rho^2 + 2\alpha_e \rho\right]^{0.5}$$

$$\rho = \frac{A_s}{(b.d)} \qquad z = d - \frac{x}{3}$$

$$\sigma_s = \frac{M_s}{(A_s.z)}$$

- k_1 = 0,8 high bond
  = 1,6 plain
- k_2 = 0,5 for bending
  = 1,0 for pure tension
- k_3 = 3,4 (National annex)
- k_4 = 0,425 (National annex)

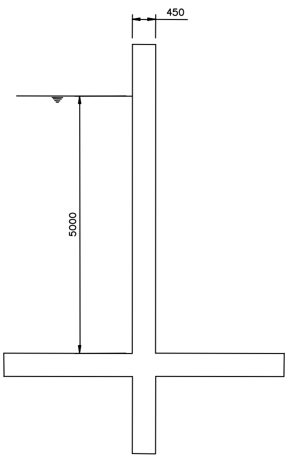
Example

EN1992

h_D = 5m depth of liquid

h = 0,45m wall thickness

- h_D/h= 11,11
- Therefore interpolate
  w_k=0,2–(11,11-5)x(0,2-0,05)/(35-5)
  = 0,169mm



BS8007

Design crack width = 0.2mm

Example – Crack Width

Determine stress in reinforcement

$$\alpha_e = \frac{E_s}{E_{cm}} \qquad \rho = \frac{A_s}{(b.d)}$$

$$\frac{x}{d} = -\alpha_e\rho + \left[\alpha_e^2\rho^2 + 2\alpha_e\rho\right]^{0.5}$$

- A_s =2093mm²
- M_s =208kNm
- α_e =200/{22x[(30+8)/10]$^{0.3}$}=6,09
- ρ =2093/(1000x400)=0,00523
- x ={6,09x0,00523+[6,09²x0,00523²+2x 6,09x0,00523]$^{0.5}$}x400 =89,1mm
- z =400-89,1/3 = 370mm
- σ_s =208x10⁶/(2093x370) =268,6N/mm²

$$z = d - \frac{x}{3}$$

$$\sigma_s = \frac{M_s}{(A_s.z)}$$

Example – Crack Width

Now calculate expression

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \frac{f_{ct,eff}}{\rho_{p,eff}}\left(1 + \alpha_e\rho_{p,eff}\right)}{E_s} \geq 0,6\frac{\sigma_s}{E_s}$$

- Long term k_t =0,4
- For 28 days, $f_{ct,eff}$ = f_{ctm}=2,9
- $A_{c,eff}$= b x $h_{c,ef}$ where
  $h_{c,ef}$ = lesser of 2,5(h-d), (h-x)/3 or h/2 = 125mm, 120,3mm or 225mm
- $\rho_{p,eff}$ =2053/(1000x120,3) = 0,01706

(ε_{sm} –ε_{cm})= [268,6 – 0,4x2,9/0,01706x(1+ 6,09x0,01706)]/200 = 0,000973

Min value = 0,6x268,6/(200x10⁶)= 0,000806

- Use (ε_{sm} –ε_{cm}) = 0,000973

Example – Crack Width

Now calculate expression

$$s_{r,\max} = k_3 c + \frac{k_1 k_2 k_4 \phi}{\rho_{p,eff}}$$

- k_1 = 0,8 high bond
- k_2 = 0,5 for bending
- k_3 = 3,4 (National annex)
- k_4 = 0,425 (National annex)
- Cover, c = 40mm
- ϕ = 20mm
- Now spacing ≤ 5(40+20/2) = 250mm [otherwise use $s_{r,max}$ =1,3(h-x)]
- Then

$s_{r,max}$ = 3,4x40 + 0,8x0,5x0,425x20/ 0,01706 = 331mm

Example – Crack Width

Now calculate expression

$$w_k = s_{r,\max}(\varepsilon_{sm} - \varepsilon_{cm})$$

- w_k = 331 x 0,000973 = 0,322mm

As this is greater than 0,169mm Not acceptable

Changing the bars to B25 at 125 centres
gives w_k = 0,138mm < 0,169mm
(Note: B25 at 140mm centres give w_k= 0,164 mm)

For reference BS8007 would require B25 at 150 to meet this design

Thermal Cracking

Minimum Reinforcement Areas

- Unless a more rigorous calculation shows lesser areas to be adequate, the required minimum areas of reinforcement may be calculated as follows:

$A_{s,min}\ \sigma_s = k_c\ k\ f_{ct,eff}\ A_{ct}$

A_{ct} = Area of concrete within tensile zone
σ_s = Absolute value of the maximum stress in reinforcement = f_{yk}
$f_{ct,eff}$ = f_{ctm} (assuming 28 days)
k = coefficient for effect of non-uniform self-equilibrating stresses, which lead to a reduction of restraint forces
k_c = pure tension = 1,0
= rectangular sections = $0{,}4\left[1-\dfrac{\sigma_c}{k_1(h/h^*)\,f_{ct,eff}}\right]$

Minimum Reinforcement Areas

- EN1992

$$\rho_{euro} = \frac{f_{ct,eff}}{\sigma_s} = \frac{f_{ctm}(t)}{f_{yk}}$$

$$f_{ctm}(t) = (\beta_{cc}(t))^{\alpha} . f_{ctm}$$

$$\beta_{cc}(t) = \exp\left\{ s \left[1 - \left(\frac{28}{t} \right)^{0.5} \right] \right\}$$

  - $A_{s,min}$ = [k_c k A_{ct}]. ρ_{euro}

Now for C30/37 concrete at 3 days

  - f_{ctm}=2,9 therefore f_{ctm}(3)=1,73
  - ρ_{euro}= *0,00346*

- BS8007

$$\rho_{crit} = \frac{f_{ct}}{f_y}$$

  - A_s = [A_c]ρ_{crit}

Now for C35A concrete at 3 days

  - Table A.1 (Grade 460)
  - ρ_{crit}= *0.0035*

Minimum Reinforcement Areas

- EN1992
  - $A_{s,min}$ = [k_c k A_{ct}]. ρ_{euro}

Now C660 recommends

	External restraint	Internal restraint
k_c	1,0	0,5
k	=1,0 <300mm =0,75 >800mm	1,0
A_{ct}	0,5h	0,2h

Therefore for a 600mm section

Internal restraint dominant

$A_{s,min}$ = 0,5x1,0x(0,2x600x1000)x0,00346

= 208mm² per face

External restraint dominant

$A_{s,min}$ = 1,0x1,0x(0,5x600x1000)x0,00346

= 1038mm² per face

- BS8007
  - A_s = [A_c]ρ_{crit}

Now this sets limitations on A_c

  - For section <500mm = h
  - For section >500mm each face controls 250mm (ie h=500mm)

- for C35A concrete at 3 days
  - Table A.1 (Grade 460)
  - ρ_{crit}= *0.0035*

Therefore for a 600mm section

A_s = (250x1000)x0.0035

= 875mm² per face

Thermal Cracking

Method following the requirements of EN1992-1-1 and EN1992-3 involves four principal steps

1. Define the allowable crack width associated with early-age thermal cracking
2. Estimate the magnitude or restrained strain and the risk of cracking
3. Estimate the crack-inducing strain
4. Check reinforcement of crack control, crack spacing and width

Thermal Cracking – Step 1

Define crack width

- This has been looked in previous section but to summarise

Limit State	Limiting crack width (mm)	Comments
Durability	0,3	For all exposure condition except X0 and XC1 (which is 0,4)
Serviceability (in water retaining structures)	0,05 to 0,2	For sealing under hydrostatic pressure
Appearance	0,3 or greater	Depends upon specific requirements for appearance

Thermal Cracking – Step 1 contu..

Define crack width

- It is important to appreciate that values in previous table are total crack widths arising from early-age deformation, long-term deformations and loadings.

- It should be noted that it has not been common practice to add early-age crack widths to those arising from structural loading

Thermal Cracking – Step 2

Estimate the magnitude of restrained strain

- The following information is required:
- Early-age temperature change in the concrete T_1
- Long term ambient temperature change T_2
- Early age temperature differential ΔT
- Thermal expansion coefficient of concrete α_c
- Autogenous shrinkage ε_{ca}
- Drying shrinkage ε_{cd}
- Restraint R
- Tensile strain capacity ε_{ctu}
- Effect of creep on stress and strain relaxation K_1
- Effect of sustained loading on tensile properties K_2

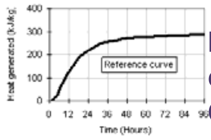
Thermal Cracking – Step 2

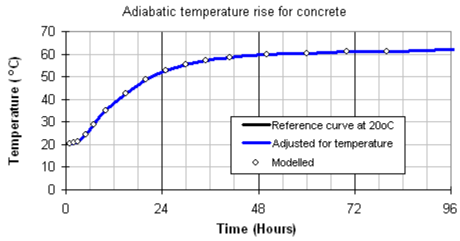
Adiabatic temperature rise

Cells for input data

Binder content	350	(kg/m³)
Binder type	fly ash	
Addition	30	(%)
Density	2400	(kg/m³)
Specific heat	1	kJ/kg°C

Temperature drop T_1 26 °C





From Spreadsheet on CD with CIRIA C660 publication

This sheet is linked with the next slide where it determines the differential

Thermal Cracking – Step 2

TEMPERATURE RISE AND DIFFERENTIALS

Cells for input data

Element details

Pour thickness		450	mm
Formwork type		18mm plywood	
Wind speed		4	m/s
Surface conductance		5.2	W/m²K
Formwork removal		36	hours

Concrete properties

Thermal conductivity	1.8	W/m°C

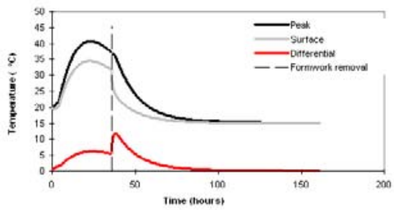
Temperature

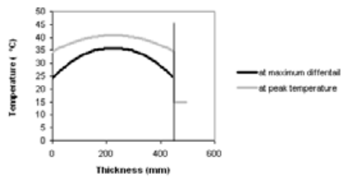
Placing temperature		20	°C
	Minimum	15	°C
Ambient temperature	MEAN	15	°C
	Maximum	15	°C
Placing time (24 hour clock)		12	hours

Temperature OUTPUT

Maximum temperature		41	°C
	at time	23	hours
Maximum differential		12	°C
	at time	38	hours

Temperature drop T_1 26 °C





Thermal Cracking – Step 2

- Concrete cast in Summer $T_2 = 20^oC$
  Concrete cast in Winter $T_2 = 10^oC$
- Thermal expansion coefficient of concrete

Thermal expansion coefficient of concrete

Table 4.4 *Coefficients of thermal expansion (Browne, 1972)*

Coarse aggregate/ rock group	Thermal expansion coefficient (microstrain/°C)		
	Rock	Saturated concrete	Design value
Chert or flint	7.4–13.0	11.4–12.2	12
Quartzite	7.0–13.2	11.7–14.6	14
Sandstone	4.3–12.1	9.2–13.3	12.5
Marble	2.2–16.0	4.4–7.4	7
Siliceous limestone	3.6–9.7	8.1–11.0	10.5
Granite	1.8–11.9	8.1–10.3	10
Dolerite	4.5–8.5	Average 9.2	9.5
Basalt	4.0–9.7	7.9–10.4	10
Limestone	1.8–11.7	4.3–10.3	9
Glacial gravel	–	9.0–13.7	13
Lytag (coarse and fine)	–	5.6	7
Lytag coarse and natural aggregate fines	–	8.5–9.5	9

Thermal Cracking – Step 2

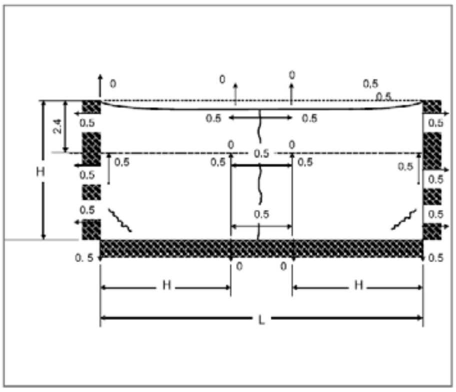
- Concrete cast in Summer $T_2 = 20^oC$
  Concrete cast in Winter $T_2 = 10^oC$
- Thermal expansion coefficient of concrete
  $\alpha_c = 10\mu\varepsilon/^oC$
  If unknown recommend $\alpha_c = 12\mu\varepsilon/^oC$
- Autogenous shrinkage, ε_{ca}
  This is based on age of concrete
  $\varepsilon_{ca(t)}=\beta_{as(t)}.\varepsilon_{ca(\infty)}$
  where $\varepsilon_{ca(\infty)} = 2,5(f_{ck}-10) = 50$ and $\beta_{as(t)} = 1\text{-exp}(-0,2.t^{0.5}) = 0.292$
  - For C30/37 at 3 days $\varepsilon_{ca(3)} = 15\mu\varepsilon$
  - For C30/37 at 28 days $\varepsilon_{ca(28)} = 33\mu\varepsilon$

Thermal Cracking – Step 2

- Drying shrinkage, ε_{cd}
  $\varepsilon_{cd(t)}=\beta_{ds(t,ts)}k_h\varepsilon_{cd,0}$

  This only applies when causing differential contraction
  or when the sections acting integrally are subject to external restraint
- Restraint, R

Thermal Cracking – Step 2



(d) Alternate bay wall construction (with construction joints)

Thermal Cracking – Step 2

- Drying shrinkage, ε_{cd}
  $\varepsilon_{cd(t)} = \beta_{ds(t,ts)} k_h \varepsilon_{cd,0}$
  - This only applies when causing differential contraction
  - or when the sections acting integrally are subject to external restraint
- Restraint, R = 0,5
- Tensile strain capacity, ε_{ctu}
  $\varepsilon_{ctu} = 1{,}01(f_{ctm}/E_{cm}) \times 10^{-6} + 8.4\mu\varepsilon$
  Determining the parameters within this formula is usually by testing and CIRIA C660 has an Appendix (A.6) dedicated to this

Thermal Cracking – Step 2

- Effect of creep on stress and strain relaxation
  - This is modifier to reduce the strain by 35%
  - K_1= 0,65
- Effect of sustained loading on tensile properties
  - Concrete under sustained tensile stress will fail at a load that is significantly lower
  - Test demonstrate stress exceed about 80% of the shorth term tensile strength
  - Thus at early-age a value of K_2=0,8 is used

Thermal Cracking – Step 3

- External restraint
  - Estimate the crack-inducing strain, ε_{cr}
    - Early-age cracking, $\varepsilon_{cr} = \varepsilon_r - 0.5\varepsilon_{ctu}$
    - where $\varepsilon_r = K_1\{[\alpha_c T_1 + \varepsilon_{ca}]R_1 + \alpha_c T_2 R_2 + \varepsilon_{cd} R_3\}$
- Internal restraint
  - Estimate the crack-inducing strain, ε_{cr}
    - Early-age cracking, $\varepsilon_{cr} = \varepsilon_r - 0.5\varepsilon_{ctu}$
    - where $\varepsilon_r = K_1 \Delta T \alpha_c R$
      - R=0,42

Internal Restraint

External edge restraint

Thermal Cracking – Step 4

- Check reinforcement of crack control, crack spacing and width
- Information required
  - Tensile strength of the concrete — f_{ct}
  - The minimum are of reinforcement — $A_{s,min}$
  - The steel ratio for calculation crack width — $\rho_{p,eff}$
  - The relationship between tensile strength, f_{ct} and the bond strength f_{bd} — k_1

Thermal Cracking – Step 4

- Tensile strength of the concrete
  - $f_{ct} = f_{ctm}$

$$f_{ctm}(t) = (\beta_{cc}(t))^{\alpha} . f_{ctm}$$

- Minimum area of reinforcement,
  - $A_{s,min}$
- The steel ratio for calculating crack width
  - $\rho_{p,eff}$
  - Note that this will have a different steel area than the flexural cracking

$$\rho_{p,eff} = \frac{\left(A_s + \xi_1^{\,2} A_p'\right)}{A_{c,eff}} = \frac{A_s}{A_{c,eff}}$$

Thermal Cracking – Step 4

- Crack width

$$w_k = s_{r,\max}(\varepsilon_{sm} - \varepsilon_{cm})$$

- Member restrained along one edge and internal restraint
  - Crack width becomes

$$w_k = s_{r,\max}\varepsilon_{cr}$$

  - Use differing ε_{cr} for internal restraint and external restraint
- Member restrained at ends only
  - Crack width becomes

$$w_k = \frac{0{,}5.\alpha_e.k_c.k.f_{ct,eff}}{E_s}\left(1+\frac{1}{\alpha_e \rho}\right)s_{r,\max}$$

Thermal Cracking – Step 4 - Example

- Internal Restraint
  - B10 at 200 gives w_k=0,1mm
- Member restrained along one edge
  - B16 at 100 gives Early-age w_k=0,05mm
    Long term w_k=0,16mm
- Member restrained at each end
  - B25 at 100 gives Early-age w_k=0,10mm
    Long term w_k=0,16mm

Geotechnical Design

- Hydraulic Failure
  - failure by uplift (buoyancy);
  - failure by heave;
  - failure by internal erosion;
  - failure by piping.

Hydraulic Failure

Hydraulic Failure

Hydraulic Failure

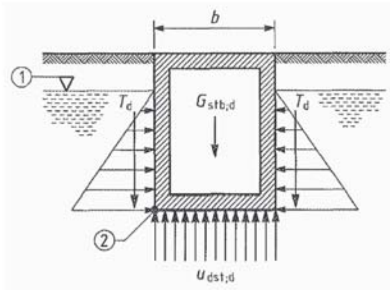
Geotechnical Design

- 2.4.7.4 Verification procedure and partial factors for uplift

  $V_{dst,d} \leq G_{stb;d} + R_d$ (2.8)

  where

  $V_{dst,d} = G_{dst;d} + Q_{dst;d}$
- Annex A (normative)
  A.4 Partial factors for uplift limit state (UPL) verifications
  - $\gamma_{G;dst}$ = 1.1 on destabilising unfavourable permanent actions
  - $\gamma_{G;stb}$ = 0.9 on stabilising favourable permanent actions
  - $\gamma_{Q;dst}$ = 1.5 on destabilising unfavourable variable actions



a) Uplift of a buried hollow structure

1 (ground)-water table
2 water tight surface

Factor of safety of 1.22

Detailing Rules

- Section 8 and 9 of EN 1992-1-1
  - Spacing of bars
  - Anchorage of reinforcement
  - Laps and mechanical couplers
- Section 9 of EN 1992-1-1
  - Rules for particular members
    - Beams
    - Solid slabs
    - Flat Slabs
    - Columns
    - Foundations
    - Walls

Detailing Rules

Movement Joints

Conclusion

- The introduction of Eurocodes has resulted in some changes in the design process
- These changes have implications for the control of early-age thermal cracking
- Crack widths can be more onerous

DESIGN OF WATER RETAINING STRUCTURES TO EUROCODES

Any Questions?