4D7 2014 - CRIB

Q1(a) Reducing the carbon footprint of concrete

Modifications to the manufacturing process to reduce CO_2 production:

Cement replacement methods

1. Adopt 5-10% MgO (Magnesium oxide) mixed with remainder OPC.
   - this reduces amount of OPC used (i.e. cement replacement)
   - % of MgO can be increased significantly above these levels but strength & durability may decrease as a result.

2. Replace OPC by (up to 30%) pfa (pulverised fuel ash)
   - this is a by-product of coal-fired power stations.

   Can also replace % of OPC by ggbs (ground granulated blast-furnace slag) - typically up to ~40%.
   - this is a by-product of steel manufacturing process.

These replacements all lead to less OPC production, which is very carbon intensive.

If too large a % of replacement materials are used, it is possible that the strength of the resulting concrete will reduce. In practice, the use of pfa + gbfs are replacement for OPC has been shown to improve the durability of concrete by providing a more impervious product. It also leads to reduced heat of hydration which decreases the potential for shrinkage cracking when cooling.

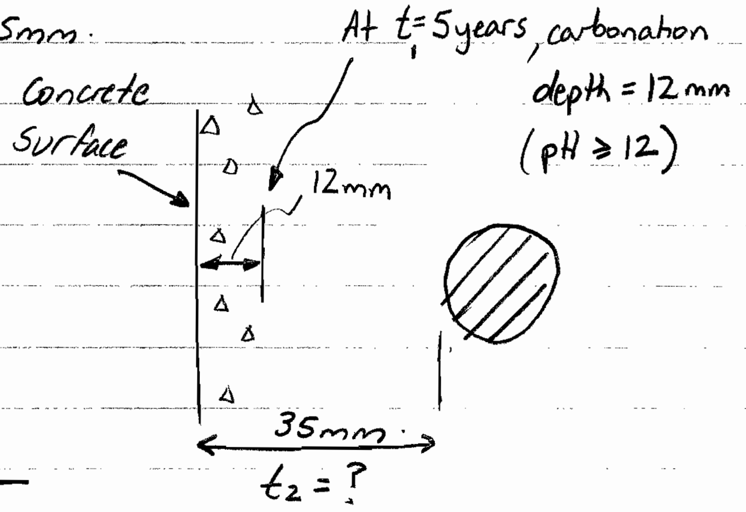
Energy reduction methods (no effect on WLP of concrete)

3. Adopt "dry process" for production of cement instead of "wet process" as this requires significantly less energy input.
   - can also slightly reduce kiln temperature to ~1300-1350°C. to reduce energy consumed in production.
4. Use recycled aggregates in concrete production, since considerable amount of energy is consumed in producing + transporting aggregates.

407 2014 - CRIB

Q1(b)(i) Reinforcement Corrosion

$t_0 = 1960$ Cover $= 35mm$



Assume $C_0 = \text{constant}$

$D = \text{constant}$

Thresholds.

NB: $pH = 12$ + $Cl^- = 0.4\%$.

Carbonation Rate $\propto \sqrt{t}$

$12mm \propto \sqrt{5}$

$35mm \propto \sqrt{t_2}$

$$\sqrt{\frac{t_2}{5}} = \frac{35}{12} \Rightarrow t_2 = \left(\frac{35}{12}\right)^2 .5 = 42.5 yrs$$

Carbonation induced corrosion can be expected after 42.5 years

Chlorides

$x_1 = 10mm$ $C_1 = 0.2\%$ $t_1 = 2$ years

$x_2 = 10mm$ $C_2 = 0.6\%$ $t_2 = 8$ years.

$x_3 = 35mm$ $C_3 = 0.4\%$. $t_3 = ?$ years.

$$C = C_0\left(1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right) = C_0(1 - erf(z))$$

$$C_1 = C_0\left(1 - erf\frac{10}{2\sqrt{D.2}}\right) = 0.002$$

$$C_2 = C_0\left(1 - erf\frac{10}{2\sqrt{D.8}}\right) = 0.006.$$

$$\frac{0.006}{0.002} = \frac{1 - erf(z_2)}{1 - erf(z_1)} = 3 \quad (1)$$

$z_1 = \frac{10}{2\sqrt{D.2}}$ $z_2 = \frac{10}{2\sqrt{D.8}}$ $\therefore \frac{z_2}{z_1} = \frac{\sqrt{2}}{\sqrt{8}} = \frac{1}{2} \Rightarrow z_1 = 2z_2$ (2)

From Tables use trial + error to guess $z_1 = 1$ $\therefore z_2 = 0.5$

$erf(z_1) = 0.84$ $erf(z_2) = 0.52$

Q1(b)(i) cont. $\frac{1-\text{erf}(z_2)}{1-\text{erf}(z_1)} = \frac{0.48}{0.16} = 3.$ as required.

$\therefore z_1 = 1$

Want to find dist. in from surface at which $C_4 = 0.4\%$ after 2 years.

$$C_1 = C_0\left(1-\text{erf}\left(\frac{10}{2\sqrt{D.2}}\right)\right) = 0.002$$

$$C_4 = C_0\left(1-\text{erf}\left(\frac{x_4}{2\sqrt{D.t_4}}\right)\right) = 0.004 \quad \text{where } t_4 = t_1 = 2 \text{ years.}$$

$$\frac{C_4}{C_1} = \frac{0.004}{0.002} = \frac{1-\text{erf}(z_4)}{1-\text{erf}(z_1)} \quad \text{where } z_1 = 1,\ \text{erf}(z_1) = 0.84.$$

$$\therefore 1-\text{erf}(z_4) = 2(1-0.84) = 0.32$$

$$\text{erf}(z_4) = 0.68$$

From Tables for $\text{erf}(z_4) = 0.68$ $z_4 = 0.7$

$$\therefore z_4 = \frac{x_4}{2\sqrt{D.2}} = 0.7 \quad ; \quad z_1 = \frac{10}{2\sqrt{D.2}} = 1.0.$$

$\therefore z_4 = 0.7 \times 10 = 7\text{mm}$ $\therefore C_4 = 0.4\%$ at $x_4 = 7\text{mm}$ after $t_4 = 2\text{yrs}$.

Want time until $C_3 = 0.4\%$ at $x_3 = 35\text{mm}$.

Diffusion $\propto \sqrt{t}$

$x_4 \propto \sqrt{t_4}$

$x_3 \propto \sqrt{t_3}$

$$\frac{7}{35} = \frac{\sqrt{2}}{\sqrt{t_3}} \Rightarrow t_3 = \left(\frac{35}{7}\right)^2 \times 2$$

$$= 50 \text{ years}$$

$\therefore$ Chloride induced corrosion can be expected after 50 years.

c.f. 42.5 years for carbonation $\Rightarrow$ Corrosion due to carbonation after 42.5 years.

407 2014 - CRIB

CFM

Q1(b)(ii) Factors affecting time to initiation & rate of corrosion

- Quality of surface concrete in cover region.
- Availability + concentration of CO_2 + Cl^- ions.
- Surface chloride concentration (+ initial concentration)
- Diffusion coefficient (D) of concrete (in practice non-linear)
- Permeability of concrete
- Degree of saturation of concrete (moisture content)

Also - Surface coatings on concrete (silane)
- expoxy coated / galvanised rebar
- stainless steel

Main durability factors - 4C's + W/C

i.e. - compaction
- curing
- cover
- cement content

4D7 2014 - CRIB

Q2 (a) Failures of concrete structures

Large number of failure examples were presented in the lectures. These were classified by primary cause of failure

i.e. (i) Detailing & Joints - Ronan Point, Camden School for Girls
Parc des Princes, Palau Bridge
Murrah Building

(ii) Long term deterioration - Ynys-y-gwas
- Stepney school pool
- FDR Driveway

(iii) Mistakes - Ferry Bridge Cooling Towers
- North Sea Oil Platforms
- Injaka Bridge

(iv) Impact, natural disasters, scour - California, Kobe, Turkey
- Kufstein Bridge
- Tasman Bridge

(v) Inadequate code rules - de la Concorde overpass.

Details given in lecture notes. Only 3 examples required. For some of above, codes were changed as a result of lessons learned e.g. disproportionate collapse rules following Ronan Point & ban on High Alumina Cement after Stepney (& other HAC collapses). For others, human error was a primary cause which codes cannot address (Injaka).

407 - 2014 CRIB

Q2(b)(i) <u>Nuclear industry whole life performance</u>

Mix design - low w/c; high cement content (strength)
microsilica (grading, permeability);
workability with superplasticizers; consider
special cements depending on local conditions
(e.g. sulfate resistance).

Design - low crack width specification

R/f steel - CARES UK approved; possibly use stainless
steel or selective FRPs (latter less well
understood so may not be approved)
- galvanised steel +/or provision for CP, if needed.
- could use prestressed with replaceable cables or
FRP tendons.

Construction - use as much offsite manufacture + prefabricated
components as possible to increase quality
control + geometric accuracy / tolerances.
- independent onsite supervision in addition to QA.
- ensure full curing of all insitu works
- focus on 4C's + W/C - compaction, cement content,
curing, cover, w/c ratio.
- increase cover from standard 50mm to, say, 75 or 100mm.
- waterproofing / sealing of surface to protect it.

Monitoring - embedded distributed strain sensors in concrete +
also strain gauges on r/f to monitor strains.
- Include AE (acoustic emission) sensors for corrosion.
- computer vision crack monitoring

Operation - regular inspections requiring qualified "expert" inspectors

Q2b(ii) Mass concrete pour for dam

First concern would be with heat of hydration generating high temperatures. This can lead to differential temperatures and hence strains when the concrete cures, resulting in cracking & subsequent shrinkage & restraint cracking when the mix contracts on cooling. Can also cause problems of excessive pressure on formwork from expanded (hot) mix.

Several actions can mitigate the heat generated by the hydration process. These include:

(i) use of cement replacement materials e.g. pfa, ggbs, MgO – this directly leads to lower heat generation

(ii) Use of chilled water/ice in mix water to start with cold mix.

(iii) inclusion of refrigeration pipe system within casting e.g. refrigerated pipes run through the formwork to extract heat – expensive but effective

(iv) increase in reinforcement to allow for increased thermal stresses.

With large concrete pours, also need to consider:

(i) Continuity of supply – to avoid "cold joints" between consecutive pours which may result, for example, from a failed concrete pump. Hence supply aspects of pour are critical. Allow back-up pumps / power supply / critical equipment.

(ii) Early set – must ensure set is not too rapid – add retardants to mix.

(iii) Formwork pressures – can be very high during large pours & great attention must be paid to subsequent shrinkage & restraint of cooling concrete.

(iv) Shrinkage cracks – minimize these – low w/c, superplasticizers.

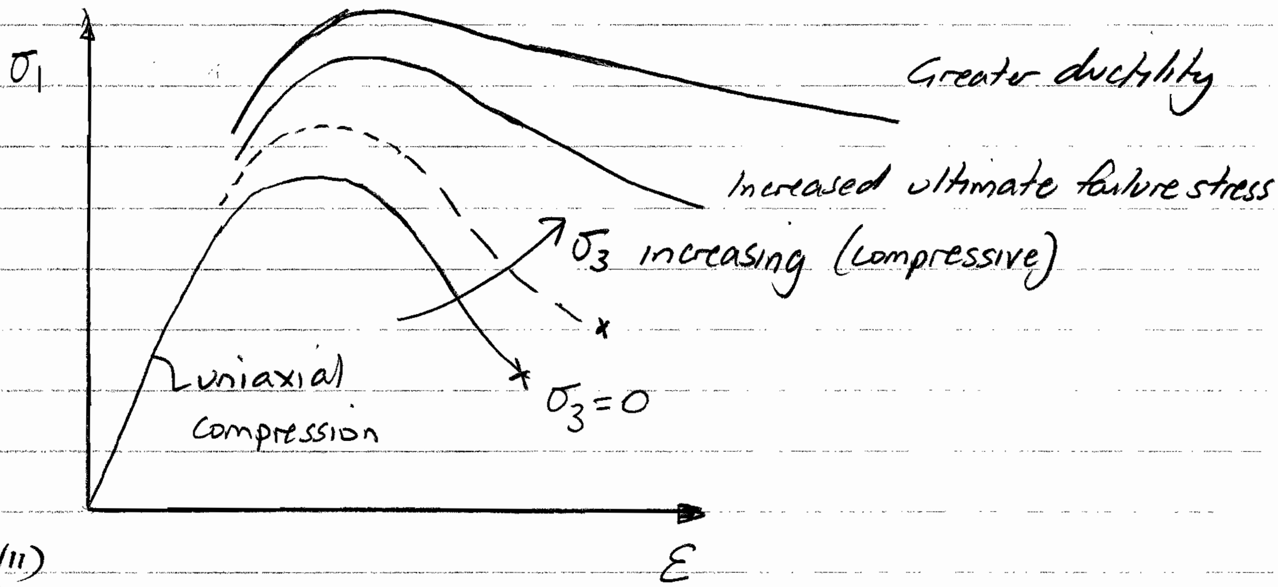
(v) Compaction – must ensure all areas of pour are accessible for compaction equipment to avoid voids. Specification of vibration & tamping methods & also use of superplasticizers for workability important.

(vi) Curing – vital for large pours to ensure full hydration of concrete.

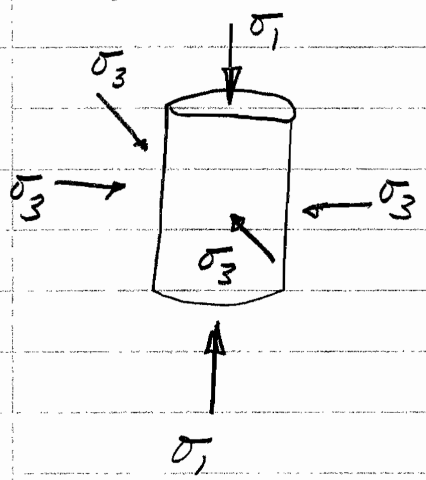
407 2014 - CRIB

crm

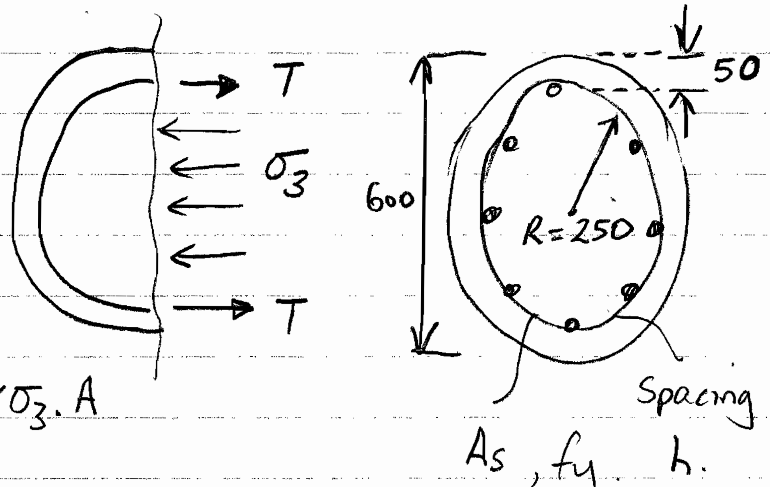
Q2(c)(i) Stress-strain curve for laterally restrained concrete



Q2(c)(ii)



FBD of half section of column



Stirrups 16 ϕ

$2T \simeq \sigma_3 . A$

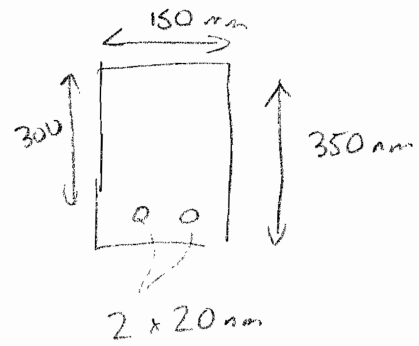
$A_s = \frac{\pi D^2}{4} = 201 mm^2$ $(200 mm^2)$

$2 . A_s f_y = \sigma_3 . 2R \, h$

$\sigma_3 \simeq \frac{f_y A_s}{h R} = \frac{500 \times 200}{100 \times 250} = 4 \text{ MPa}$

Increasing lateral constraining stress (σ_3) from zero results in increased axial strain capacity, greater ductility + higher ultimate strength.

Q3.



$E_s = 210\,GPa$

$E_c = 30\,GPa$

$A_s = 2 \times \frac{20^2 \pi}{4} = 628.3\,mm^2$

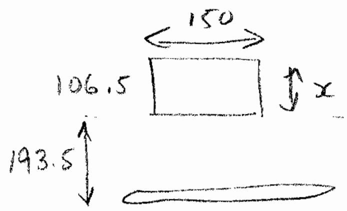
a i)

$\sigma = \frac{My}{I}$ $\quad \sigma = f_{ct}$

$M_{cr} = \frac{f_{ct} I}{y}$ $\quad I = \frac{150 \times 350^3}{12} = 535.94 \times 10^6\,mm^4$ $\quad y = \frac{350}{2}$

$= 3.0625 \times 10^6\,Nmm / f_{ct}$ $\therefore I/y = 3.0625 \times 10^6$

ii)



$m = \frac{E_s}{E_c} = \frac{210}{30} = 7$

$mA_s = 7 \times 628$
$= 4398\,mm^2$

$\frac{x^2}{2} \times 150 = 4398\,(300 - x)$

$75x^2 + 4398x - 1319469 = 0$

$x = \frac{-4398 \pm \sqrt{4398^2 - 4(75)(-1319469)}}{2 \times 75}$

$= \frac{-4398 + 20376}{150} = 106.52\,mm$

$I_{cr} = y^2 A + \frac{bx^3}{12} + \left(\frac{x}{2}\right)^2 A$ (neglect I about steel)

$= 193.5^2 (4398) + \frac{150 \times 106.5^3}{12} + \left(\frac{106.5}{2}\right)^2 \times 150 \times 106.5$

$= 164.67 \times 10^6 + 15.10 \times 10^6 + 45.30 \times 10^6$

$= 225.07 \times 10^6\,mm^4$

Q3

(a)(ii) cont.

$$\sigma_c = \frac{M_a y}{I_{cr}} \qquad \varepsilon_c = \frac{\sigma_c}{E_c} = \frac{M_a y}{E_c I_{cr}}$$

$$= \frac{M_a \cdot 106.5}{30000 \times 225.07 \times 10^6}$$

$$= 1.577 \times 10^{-11} M_a$$

$$\frac{\varepsilon_c}{106.5} = \frac{\varepsilon_s}{193.5} \quad \therefore \quad \varepsilon_s = \varepsilon_c \times \frac{193.5}{106.5}$$

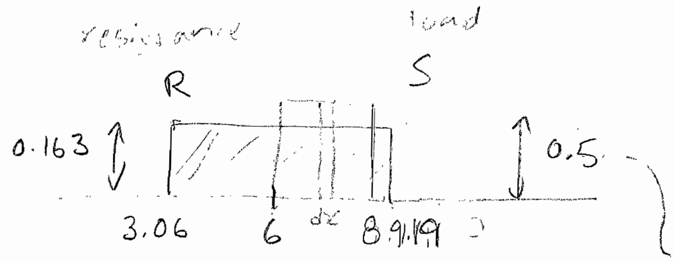
$$\varepsilon_s = 2.866 \times 10^{-11} M_a$$

b)

$f_{ct} \rightarrow 1\text{MPa} \rightarrow 3\text{MPa}$

$M_{cr}(1\text{MPa}) = 3.0625 \times 10^6 \text{ Nmm} = 3.0625 \text{ kNm}$

$M_{cr}(3\text{MPa}) = 9.187 \times 10^6 \text{ Nmm} = 9.187 \text{ kNm}$



$h_R = \frac{1}{9.19 - 3.06} = 0.164$ $\qquad h_S = \frac{1}{2} = 0.5$

probability of resistance between x + dx

$P_R = 0.163\,dx$

probability Load is greater than x

$P(S \geq) = (8 - x) h_S = 0.5(8 - x)$

$$\text{Prob fail} = P_f = \int_6^8 (8-x)\,0.5 \times 0.163\,dx + 0.163(6 - 3.06)$$

$$= 0.0815 \int_6^8 (8 - x)\,dx + 0.163 \times 2.94$$

$$= 0.0815 \left[8x - \frac{x^2}{2} \right]_6^8 = 0.163 + 0.479$$

$$= 0.642$$

3(c) bookwork from lecture notes & lectures

e.g. - corrosion - cracks } along bars
- plastic shrinkage }

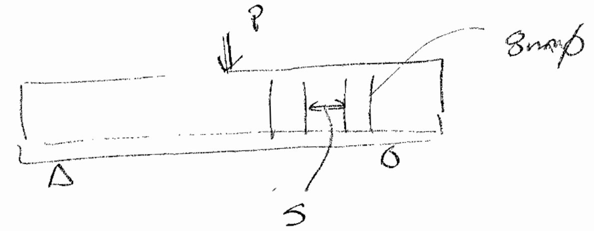
- temperature

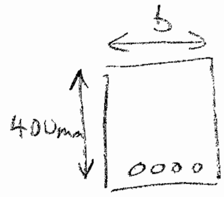
- Drying shrinkage

- ASR "Isle of Man"/Manx Cracking – "mesh" type cracks.

Give source of cracking plus characteristics of crack pattern where appropriate

Q4



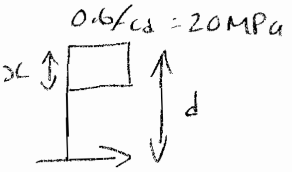


$f_{yd} = 430\,MPa$

$A_s = 4 \times \pi\, 25^2 / 4 = 1963\,mm^2$

a) $b = 250$, $s = 150\,mm$

i)



long. equil

$20\, b . x = A_s f_{yd}$

$x = 1963 \times 430 / 20 \times 250 = 168.8\,mm$

$M_U = A_s f_{yd} (d - x/2)$

$= 1963 \times 430 (400 - 168.8/2) = 266.39 \times 10^6\,Nmm$

$= 266.39\,kNm$

ii) $s = 150\,mm$ $\quad A_{sw} = \pi 8^2/4 \times 2$ (2 legs) $= 100.5\,mm^2$

assume transverse steel controls so maximise $\cot\theta$ by using shallow angle $\cot\theta = 2.5$

$V_{Rd,s} = A_{sw} f_{yd} (0.9d) \cot\theta / s$

$= 100.5 \times 430 \times 0.9 \times 400 \times 2.5 / 150$

$= 259.4\,kN$

Check concrete

$V_{Rd,max} = f_{c,max} (b_w\, 0.9d) / (\cot\theta + \tan\theta)$

$= 10 \times 250 \times 0.9 \times 400 / (2.5 + 1/2.5)$

$= 310.3\,kN > V_{Rd,s}$ ✓

Q4 (cont.)

a) iii)

$P = 400 kN$, $V = 200 kN$

At supports $M = 0$ but need to carry additional longitudinal force due to variable angle truss analogy where:

$$\Delta F_{td} = 0.5 V \cot\theta$$

if $\cot\theta = 2.5$ ∴ $\Delta F_{td} = 0.5 \times 200 \times 2.5$
$= 250 kN$

anchorage length l_a for $A_s = \frac{\pi 25^2}{4} = 490.9 mm^2$ (1Ø25)

For yield of bar

$2\pi r f_{bd} l_a = A_s f_{yd}$

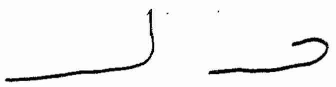
$l_a = A_s f_{yd} / 2\pi r f_{bd} = 490.9 \times 430 / 2\pi \cdot 12.5 \times 3$ **= 896mm**

$= 896 mm$

OR $\Delta F_{td} = 250 kN$, Bond $= 3 MPa$ ∴ $250 = 2\pi r . 3 . l_a \Rightarrow$ **$l_a = 265 mm$**

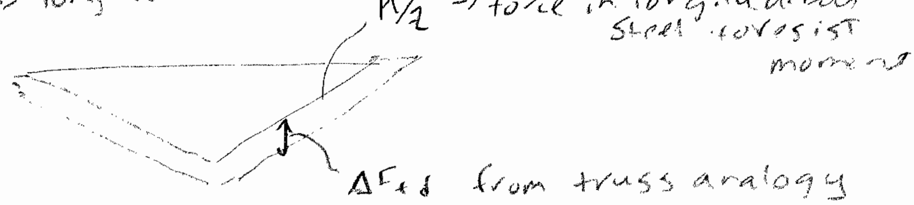
- Could reduce length using a hook/bend

e.g.



Or could also reduce $\cot\theta$ so that ΔF_{td} reduces but would need to check concrete doesn't start to control ($V_{Rd,max}$).

- BMD ⇒ long force demand



determine point where $M/2 + \Delta F_{td} = 2 \times \frac{25^2 \pi}{4} \times f_{yd}$ (2 bars, A_s)

then provide anchorage beyond that point

Q4 (b)

if looking to minimise concrete width
choose $\cot\theta = 1$

$V_{Rd,max} = f_{cmax} (b_w \, 0.9d)/(\cot\theta + \tan\theta)$

$b_w = \dfrac{200 \times 1000}{10 \times 0.9 \times 400} \times 2 = 111.1\text{mm}$

for this width
if $\cot\theta = 1$ then

$V_{Rd,s} = 100.5 \times 430 \times 0.9 \times 400 \times 1 / s$

$s = 15.56 \times 10^6 / 200000 = 77.8 \text{ mm}$

so transverse steel spacing would need to reduce
or larger diameter bars reqd.

other factors:
- sufficient space between bars
- fire resistance