BubbleDeck Design Guide for compliance with BCA using AS3600 and EC2

Prepared by: kyng consulting pty ltd

31 October 2008
Reference: DG_v.1.2

BubbleDeck® - Conditions of use of Design Guide - 31 October 2008

Set out below are the terms and conditions on which you agree to use the Design Guide provided by Kyng Consulting for BubbleDeck. They constitute a legally enforceable contract between Kyng Consulting and you. If you do not accept these terms and conditions, you must not download or use the Design Guide.

1. The following words and phrases have the meanings given to them in these terms and conditions:

(a) Kyng Consulting means Kyng Consulting Pty Ltd as trustee for the Karim Yngstrom Family Trust (ABN 86 910 212 277).

(b) BubbleDeck means BubbleDeck Australia & New Zealand Pty Ltd.

(c) BubbleDeck System means the two-way hollow void former technology owned by BubbleDeck and described in the Design Guide.

(d) Design Guide means the design guide for the BubbleDeck System.

(e) Purpose means the use of the Design Guide in connection with use of the BubbleDeck System pursuant to a licence from BubbleDeck or a licensee of BubbleDeck.

(f) you means the company or individual downloading a copy of the Design Guide under these terms and conditions.

Licence

2. Kyng Consulting grants to you a non-exclusive licence to download, copy and use the Design Guide for the Purpose.

3. You agree that you (or any other person associated with you):

(a) will not disclose the Design Guide to any third party except for the Purpose ;

(b) will not use the Design Guide for any purpose other than the Purpose;

(c) will not copy or otherwise reproduce the Design Guide except for the Purpose;

(d) will on demand by Kyng Consulting immediately return to Kyng Consulting or its nominee any and all copies of the Design Guide and any documents created by or for you which substantially reproduce the Design Guide;

(e) will only disclose the Design Guide to your officers and employees who need to have access to the Design Guide for the Purpose;

(f) will procure that your officers and employees are made aware of the your obligations in relation to the Design Guide and that each officer and employee must comply with such obligations.

4. You must not use the Design Guide in connection with the use of any building system of any third party similar to the BubbleDeck System.

Intellectual property

5. Kyng Consulting retains ownership of all intellectual property subsisting in or contained in the Design Guide including (without limitation) the copyright in all drawings, specifications or other material contained in the Design Guide. BubbleDeck retains ownership of the rights to the trade mark "BubbleDeck".

6. You must not use any Kyng Consulting or BubbleDeck intellectual property except for the Purpose. You must not use any Kyng Consulting or BubbleDeck intellectual property in connection with any building system of any third party similar to the BubbleDeck System.

7.   BubbleDeck will own the intellectual property rights in any improvements made to the BubbleDeck system created by you pursuant to the use of the information contained in the Design Guide.

Warranties and liability

8. Kyng Consulting warrants that it has used reasonable endeavours to ensure that the Design Guide is accurate.

9. To the extent permitted by law, Kyng Consulting does not warrant that the Design Guide is error free or fit for the purpose of use by you. You acknowledge that it is your responsibility to check that the information contained in the Design Guide is accurate and suitable for use by you. You accept that, to the extent permitted by law, Kyng Consulting accepts no liability for any errors arising out of the use Design Guide.

10. Except to the extent that any law or statute prohibits the exclusion of any condition or warranty, all other conditions or warranties are excluded. Where any law or statute implies a term into this agreement, or confers a right or remedy, which cannot be excluded, the liability of Kyng Consulting is limited to the maximum extent allowed under the applicable law or statute.

11. Kyng Consulting's liability and your remedy for breach of any express warranty, or warranty or right implied or conferred by law which cannot be excluded, is limited to, at Kyng Consulting's option, one or more of (a) supplying the Design Guide again; or (b) payment of the cost of having the Design Guide supplied again.

12. Except as expressly provided elsewhere in this agreement, Kyng Consulting will be under no liability to you (whether for breach of contract, negligence or otherwise) in respect of any loss or damage which may be suffered or incurred by you or which may arise directly or indirectly in respect of the supply or use of the Design Guide.

13. Without limiting the generality of clause 12 above, Kyng Consulting will be under no liability to you (whether for breach of contract, negligence or otherwise) for any special, incidental, indirect, or consequential damages whatsoever (including, without limitation, damages for loss of business or profits, loss resulting from business interruption, loss of business information, loss resulting from any claim by any third party or any other pecuniary loss) arising out of the supply of the Design Guide or its use, even if Kyng Consulting has been advised of the possibility of such damages

14. You are responsible for complying with any law, legislation, regulation or code of practice applicable to the use of the Design Guide by you. Kyng Consulting is not responsible for, and excludes liability for, any breach of any applicable law, legislation, regulation or code of practice by you in relation to use of the Design Guide.

15. If any term or part of these terms and conditions is, or becomes, for any reason invalid or unenforceable at law, that term or part of these terms and conditions will be and is hereby deemed to be severed from these terms and conditions without affecting the remainder of these terms and conditions and the remainder of these terms and conditions will continue to be valid and enforceable.

16. These terms and conditions are governed by and are to be construed in accordance with the laws of Western Australia. Each party irrevocably and unconditionally submits to the non-exclusive jurisdiction of the courts of Western Australia.

Background

BubbleDeck is a slab system that has become very popular in Europe and around the world in the past decade. The system was invented in Denmark after a government sponsored competition looked for new ways to constructing buildings, and in particular new ways to enhance the flexibility and efficiency of design using pre-fabricated techniques. BubbleDeck won the competition and was successfully introduced to large scale commercial construction in 1999 on the Wena tower in Rotterdam, Holland. For the first time, it was possible to prefabricate a two-way concrete slab economically. This report presents the results of international research into the section properties of BubbleDeck slabs, and proposes methods that allows it to be designed to satisfy the requirements of the Building Code of Australia (BCA), using first principles and international design guidance.

BubbleDeck is generally designed using conventional design methods for solid slabs in accordance with current local standards of design and good practice. The guidance included in this report is based on the best practice for the design of BubbleDeck derived through experimental data and practical expertise carried out in Denmark, Holland and Germany, and which has been adopted by the Standards Authorities in the respective country. The recommendations from the research has also been endorsed by the British Standard Institute in the UK, which recommends that BubbleDeck be treated as a solid slab, with due regards to the impact of the void formers.

The following adjustments must be made to allow for the effect of the void formers, or bubbles:

- The Dead Load, G, of the structure is significantly reduced;
- The stiffness of the slab is adjusted for both cracked and uncracked condition;
- The shear capacity is reduced in the voided areas of the slab; and
- The punching shear calculations are as for a flat slab, as the slab is left solid around the columns. The author of this paper recommends the designers follow the guidance of Eurocode 2 - BS EN 1992-1-1:2004 (EC2) for the design of punching shear as the Australian Standard AS 3600-2001 results in undesirable complex site detailing when using flat slabs, as noted by *Rangan et al* in *"Concrete Structures", p573*.

This paper relates the recommendations made by the European Standards Authorities for the design of BubbleDeck slabs for practical use with AS 3600.

BubbleDeck slab profiles and characteristics

BubbleDeck slabs can theoretically be manufactured to any profile, but experience around the world has shown that the following 5 cross sections cover most building applications.

Version	Slab Thickness	Bubbles	Span (Multiple bays)	Cantilever Maximum Length	Span (Single bays)	Completed Slab Mass	Site Concrete Quantity
	mm	mm	metres	metres	metres	Kg/m²	m³/m²
BD230	230	Ø 180	5 – 8.1	≤ 2.2	5 – 6.3	370	0.11
BD280	280	Ø 225	7 – 10.1	≤ 2.7	6 – 7.8	460	0.14
BD340	340	Ø 270	9 – 12.5	≤ 3.3	7 – 9.6	550	0.18
BD390	390	Ø 315	10 – 14.4	≤ 3.8	9 – 11.1	640	0.21
BD450	450	Ø 360	11 – 16.7	≤ 4.5	10 – 12.5	730	0.25

BubbleDeck has been successfully used as transfer slabs with depths of over 600mm. Mega-spans can be achieved when combined with post tensioning, as was the case for the Danish Radio complex in Copenhagen (DR-Byen).
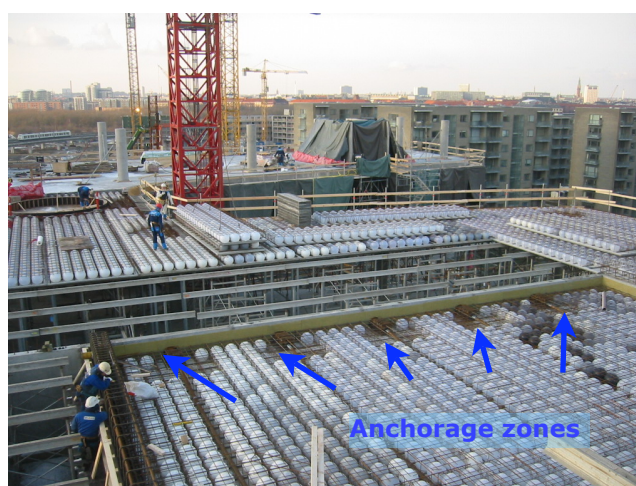
*DR-Byen project showing prestressing tendons integrated with BubbleDeck slabs*

BubbleDeck can be implemented as one of three alternatives:

1. **In-situ application** - BubbleDeck slabs can be constructed as in-situ slabs. The "bubbles" are placed in modules of top and bottom steel and are effectively held in place. The modules are then placed on conventional formwork, and the slab is poured in two parts; a first shallow pour is carried out to provide enough weight to resist the uplift force on the bubbles. A second pour, usually one day after the first pour, completes the slab. The in-situ alternative can be very attractive for projects where the finished soffit of the slab is domed or curved, or where access is restricted.

2. **Precast elements** - BubbleDeck slabs can be delivered to site as fully precast elements. This options would still allow the substantial materials savings provided by BubbleDeck, but it would limit the two-way benefit aspects of the slab, if the spans under consideration are larger than the precast element. The two way action can be maintained by designing appropriate connections between the elements.

3. **Semi-precast elements** - The most effective delivery method for BubbleDeck slabs is through the use of semi-precast elements. These include the bubbles, and most of the main reinforcement for the slab. The elements are then stitched on site through a concrete pour. The semi-precast system offers great cost benefits, and it provides a unique solution for achieving precast two-way spanning slabs.

Design for durability - Section 4 of AS 3600

All the recommendations in Section 4 of AS 3600 are unaffected by the use of void formers in the slab. The guidance therein applies to BubbleDeck slab design, and minimum cover for exposure classification shall be determined accordingly. Note that when semi-precast minimum cover at BubbleDeck splices is achieved through adequate detailing of precast element.
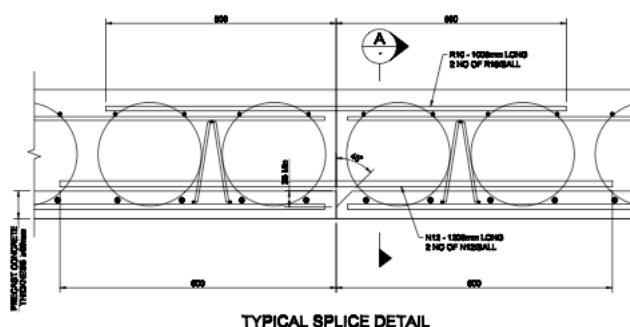
Typical splice detail ensuring minimum cover for both fire and durability requirements

## Design for fire resistance - Section 5 of AS 3600

Recommendations from the CSIRO using conservative analysis tools (2D model) to model fire loads in accordance with AS 1530.4 has shown that for BD280 slabs and above, a 120 minutes rating is achieved using the same provisions defined in Tables 5.5.1 and 5.5.3(A) of AS 3600. The same provisions can also be used for BD 230 slabs up to 90 minutes fire periods. (refer to CSIRO conclusions report)

System	Simply Supported Slab	Continuous Slab	
	Cover to bottom reinforcement (mm)	Cover to bottom reinforcement (mm)	FRL
BD230	20	15	60/60/60
	25	15	90//90/90
	30	15	120/120/90
BD280	20	15	60/60/60
	25	15	90//90/90
	30	15	120/120/120
	45	25	180/180/120
BD340	20	15	60/60/60
	25	15	90//90/90
	30	15	120/120/120
	45	25	180/180/120
	55	35	240/240/120
BD390	20	15	60/60/60
	25	15	90//90/90
	30	15	120/120/120
	45	25	180/180/180
	55	35	240/240/180
BD450	20	15	60/60/60
	25	15	90//90/90
	30	15	120/120/120
	45	25	180/180/180
	55	35	240/240/240

Table extracted from CSIRO report FCO 2645 on BubbleDeck Fire Performance dated 24 June 2008

The CSIRO assessment was generally governed by the insulation performance of the slab. Noting that the modelling was performed on a 2D basis, which assumed the void to be continuous along the section of the slab, a large degree of conservatism was introduced in the results. The voids formed in BubbleDeck slabs are discreet, and hence they would not provide the thermal bridging that a prismatic void would, as assumed by the CSIRO analysis.

More detailed analysis carried out on the BD 280 slab (using 3D modelling capabilities) has shown that BD280 slab exceeds the requirements of AS 1530.4 for 180 minutes period and hence performs in accordance with section 5 of AS 3600 for up to 180 minutes.
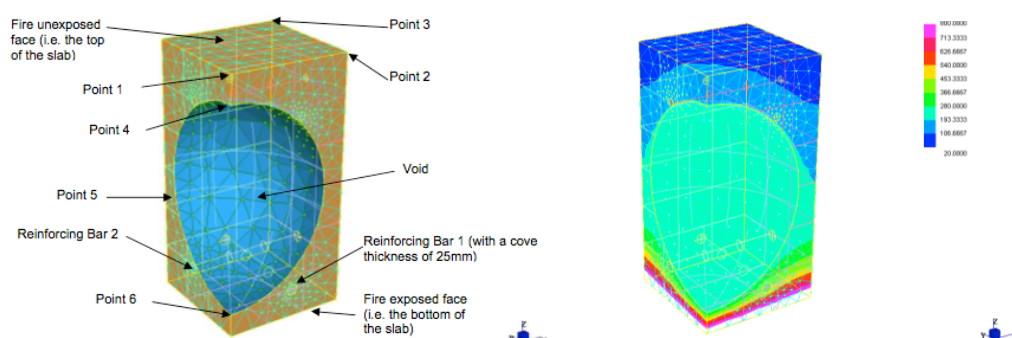
3D model of BD 280 slab by Arup with temperature distribution after 180 minutes

The CSIRO table shown above can be used conservatively in the preliminary phases of the design. 3D analysis of the slab demonstrates that the provisions of AS 3600 Section 5 are also applicable to most BubbleDeck slabs. The effective thickness of the BubbleDeck slab for determining insulation in Table 5.5.1 can be approximated as the total volume of concrete in one square meter of slab divided by one square meter of slab.

It is recommended that for the thinner BubbleDeck slabs, BD 230 and BD 280, an assessment is undertaken for the actual slab section profile by a reputable Fire Engineer in order to confirm the fire performance, when this is required to be above 90 minutes or 180 minutes respectively.

Structural analysis - Section 7 of AS 3600

BubbleDeck slabs behave isotropically, and hence they can be analysed using the same methods used for solid two-way slabs. The recommendations of Section 7 of AS 3600 can be used with the following provisions for the section properties of the slab.

Bubbledeck section properties

The typical BubbleDeck module is defined by the parameters a and D, where a is a measure representing the matrix of the void formers in the slab and D is the overall depth of the slab.
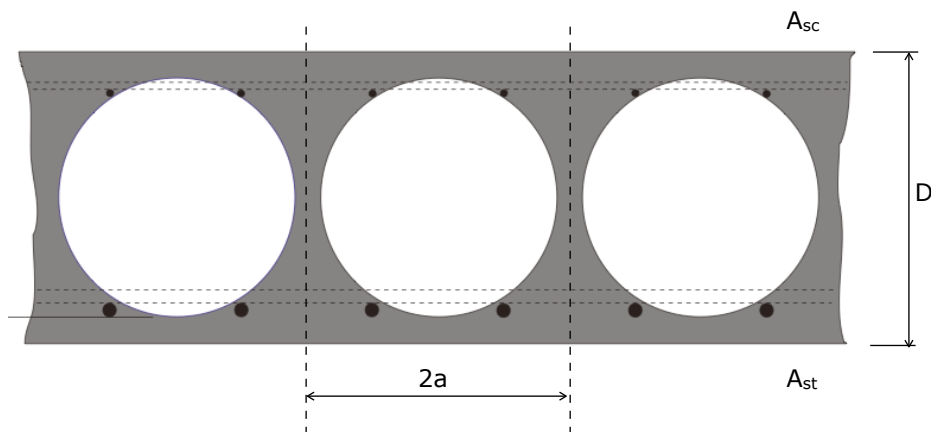
Basic Bubbledeck Geometry

Uncracked section properties

The second moment of area for the concrete part of the slab $I_{BD,conc}$ can be expressed through the simple formula (*Darmstadt University of Technology*, *Investigation of BubbleDeck slabs, Professor Dr. Ing. Martina Schnellenbach-Held*):

$$I_{BD,conc} = D^3/12 - 0.124\ a^3$$

Thus the uncracked transformed section's second moment of area can then be obtained assuming that the centre of gravity for the concrete cross section lies at D/2.

If the second moment of area $I_{eq,steel}$ of the transformed steel area $A_{eq,steel}$, made up from the top A_{sc} (compression) and bottom A_{st} (tension) reinforcement areas which centre of gravity is located at a depth $d_{eq,steel}$, the total uncracked second moment of area of the BubbleDeck section becomes:

$$I_{BD,uncracked} = I_{BD,conc} + I_{eq,steel} + A_{eq,steel} (D/2 - d_{eq,steel})^2 \; ;$$

assuming that the impact of the transformed steel on the centre of gravity of the total transformed section does not shift the centre of gravity of the concrete section significantly.

The equation above results in an approximate stiffness of the BubbleDeck slab of around 90% of that of a solid slab with the same depth.

Thus, the uncracked second moment of area can be determined for both short and long term conditions.

Cracked section properties

The effect of the voids on the cracked section properties is less than that manifested on the uncracked section. Hence, the cracked second moment of area for BubbleDeck slabs can be taken simply as:

$$I_{BD,cracked} = 0.9 \, I_{solid,cracked}$$

Thus, the cracked second moment of area can be determined for both short and long term conditions.

Structural Analysis

A structural analysis of the slab can now be carried out using the properties derived above, with due consideration to the reduced weight of the slab.

The effective second moment of area can be derived using the expression in 8.5.3.1 of AS 3600 for both short term and long term effects, using a reduced value of the cracked moment $M_{BD,cr} = 0.8 \, M_{cr}$ where the cracked moment M_{cr} is calculated using the uncracked BubbleDeck section properties. This translates to the following expression;

$$M_{BD,cr} = 0.8 \, [\, I_{BD,uncracked} / y_t \,] \, f'_{cf}$$ where y_t is the distance to the extreme tensile fibre, measured from the centroidal axis of the section (ignoring reinforcement).

Thus;

$$I_{BD,ef} = I_{BD,cracked} + (\, I_{BD,uncracked} - I_{BD,uncracked} \,) \, (M_{BD,cr} / M_s \,)^3 \leq I_{e,max}$$ where $I_{e,max}$ is as defined in 8.5.3.1 of AS 3600

The analysis can be carried out using commercial software packages through finite element analysis, or through 3D frame analysis packages modelling the slab as a grillage. It is recommended that any grillage be modelled on a 1m wide beam basis to facilitate the extraction and interpretation of results.

It is recommended that the deflection checks for the design of the slab are carried out in conjunction with the analysis of the slab. Generally, the requirements for deflection and crack width calculations become governing in the final design of the slab.

Design of BubbleDeck slabs

Once the analysis of the slab is complete, strength calculations can be carried out on the preliminary section derived from the analysis.

Strength in bending

BubbleDeck omits a significant volume of concrete (compared to a solid slab) in the central core of the slab, where stress levels are relatively insignificant when the section is in bending. When designing for flexural resistance, the depth of the stressed concrete in compression (often called the 'stress block') is concentrated within the solid concrete between the outermost extent of the bubble and the slab surface, whether the designer considers the stress block to be rectangular, recto-parabolic or other shape in accordance with accepted design methodology.
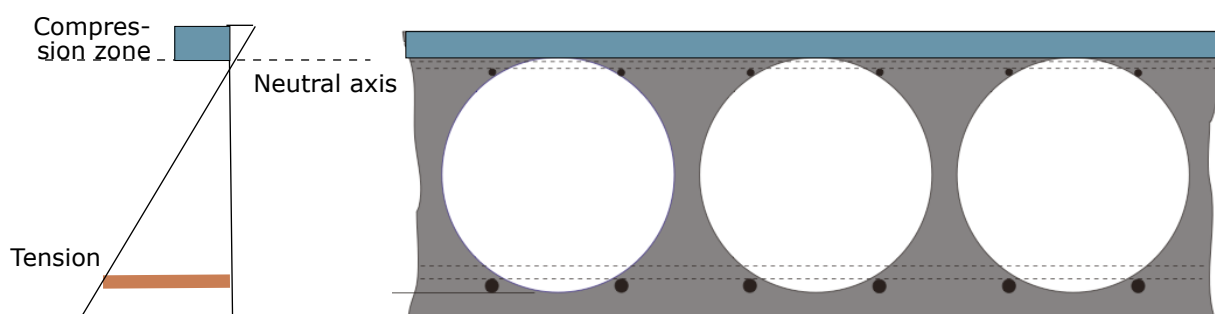
Stress distribution trough BubbleDeck under normal loading

Sometimes, in heavily stressed slabs, the stress block will encroach slightly within the bubble zone. Studies and tests have demonstrated this has an insignificant effect on the resistance of a BubbleDeck slab in normal design situations. The following recommendation has been adopted by the German Standard DIN 1045, and gives a simple check which limits the extent with which the elastic neutral axis is allowed to encroach within the bubble zone.
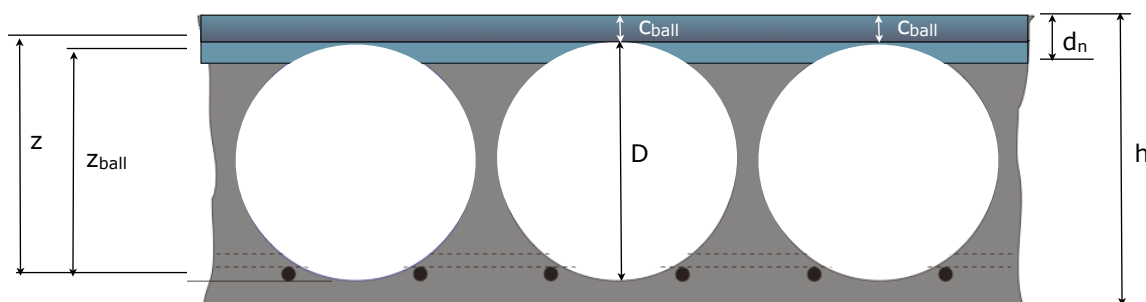
Compression zone can encroach on bubble zone for heavily reinforced slabs

In the expression below, μ_{ms} is a parameter defining the ratio of the moment resisted by the bubble zone to the total moment resisted by the cross section, M_{ball} / M_u. BubbleDeck slabs can be designed using conventional design principles if this ratio is limited to 0.20, i.e. the stresses are allowed to redistribute locally, when this ratio is less than 20%.

$$\mu_{ms} = M_u \, 1.96D / (f'_c \, h^3) \le 0.20 \; ; \text{ where}$$

D is the ball diameter
h is the depth of the slab
M_u is the design Moment

The maximum depth of the neutral axis can also be derived through the following expression, using the limiting ratio above;

$$M_{ball} / M_u = \mu_{ms} = [\, (d_n - c_{ball}) \, z_{ball} \,] / (d_n \, z) = 0.20 \; ; \text{ where}$$

M_{ball} is the contribution of moment resistance by the section within the ball zone
c_{ball} is the top cover of the ball
d_n is the depth of the neutral axis
z_{ball} is the lever arm contributing to M_{ball}
z is the lever arm contributing to M_u

Thus, the strength in bending of a BubbleDeck slab can be calculated in accordance with 9.1.1 of AS 3600, provided that the proportion of the moment resistance by the concrete within the ball zone is limited to 20%. This effectively allows for a redistribution of the moment of resistance within the slab.

Strength in shear

BubbleDeck provides the designer with great flexibility, as the discreet bubbles can be omitted locally to either allow for the location of openings or cast in elements that would otherwise interfere with the overall design of the building, such as drainage pipes and electrical conduits. It also allows the designer to provide local increased resistance of the section for areas of high shear stress as it is the case around the columns.

AS 3600 addresses the effects of shear and unbalanced moments in solid slabs through the provision of torsional beams within the slab. The detailing of such reinforcement can become complex for thinner slabs, and becomes unpractical when using a semi precast system such as the BubbleDeck semi precast elements, where the torsional reinforcement can lose its continuity through the splices. For this reason, it is recommended that codes of practice that use punching shear perimeter design be used, such as BS 8110 or the more up to date Eurocode 2 - BS EN 1992-1-1:2004 (noted EC2 hereafter), available from SAI Global. The use of section 6.4 of EC2 allows for simple detailing around the columns, and effectively increases the effective column head by providing shear reinforcement along the critical shear perimeters.

Punching shear calculations

The procedure for designing for shear resistance consists of determining four main conditions, as follows:

- Checking for column shear failure at the perimeter of the column;
- Determining the extent of the solid area around the columns, i.e. the area around the columns where the bubbles are omitted;
- Determining the minimum extent of the tension steel in the column area, i.e. defining the minimum length of the steel reinforcement that is included in the shear resistance calculation of the hollow section; and
- determining the shear reinforcement and its layout, as required.

Note that as the use of EC 2 is recommended, the analysis should include one load case for shear check using the combination factors of Eurocode, namely:

$E_{d,dst} = 1.35\ G + 1.5\ Q$

Design shear magnification factor for out-of-balance forces

For structures where lateral stability does not depend on frame action between the slab and the column, and where adjacent spans do not differ in length by more than 25% the maximum design shear should be multiplied by the following factors, depending on the location of the column in the slab.

A	Internal column
B	Edge column
C	Corner column
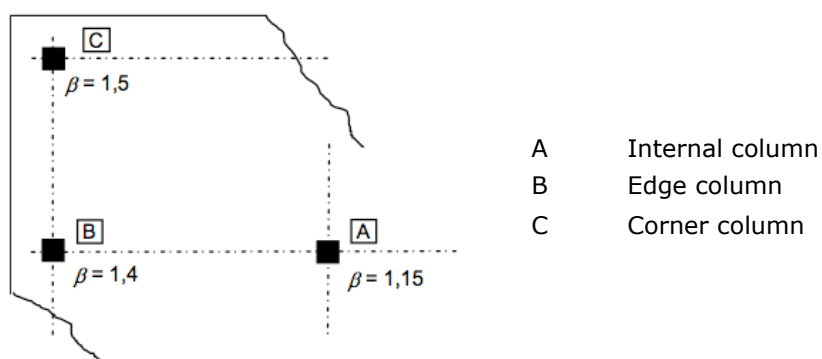
$V_{max} = \beta\ V_{Ed}$; where

$\beta =$ 1.15 for internal columns
1.4 for edge columns
1.5 for corner columns

Where the spans differ more than 25%, refer to EC2 to calculate the appropriate magnification factor.

Column shear failure

The shear stress v_{Ed} along the column perimeter should be limited to the maximum allowable shear stress in the concrete section $v_{Rd,max}$.

$v_{Ed} < v_{Rd,max}$; where   EC2 6.4.3 (2)

$v_{Ed} = \beta \, V_{Ed} \, / \, [\, u_0 \, d \,] = V_{max} \, / \, [\, u_{col} \, d_{om} \,]$;   EC2 (6.38)
$u_0 = u_{col}$ = perimeter of the column ;
$d = d_{om}$ = mean effective depth of the slab ;
$v_{Rd,max} = 0.5 \, v \, f_{cd}$;   EC2 6.4.5 (3) **Note**
$v = 0.6 \, / \, [\, 1 - (f_{ck} \, / \, 250) \,]$;   EC2 (6.6N)
f_{ck} = characteristic compressive cylinder strength at 28 days ($= f'_c$)
$f_{cd} = f_{ck} \, / \, 1.5$ = Design value of concrete compressive strength   EC2 (3.15) and 2.4.2.4

Extent of solid area around columns

The extent of the solid area around the column is determined by locating the perimeter at which the shear stress in the slab falls below the shear resistance of the hollow slab, including any tension column reinforcement.

The introduction of the voids in the slab reduces its shear strength. Studies carried out at Denmark's Technical University, Darmstadt University in Germany and Eindhoven University in Holland have shown that the shear strength of a BubbleDeck slab can conservatively be taken as the shear strength of a solid slab of the same depth multiplied by a reduction factor of 0.6.

The maximum allowable shear stress in a solid slab is determined by:

$v_{Rd,c} = C_{Rd,c} \, k \, (100 \, \rho_l \, f_{ck} \,)^{1/3} \geq v_{min}$; where   EC2 (6.47)

$C_{Rd,c} = 0.18 \, / \, 1.5 = 0.12$ EC2 6.4.4 (1) **Note**
$k = 1 + (\, 200 \, / \, d \,)^{1/2} \leq 2.0$, where
   $d = d_{om}$ = mean effective depth of the slab $(d_{ox}+d_{oy})/2$
$\rho_l = (\, \rho_{lx} \, \rho_{ly} \,)^{1/2} \leq 0.02$, where
   ρ_{lx} and ρ_{ly} are the reinforcement ratios relating to the tension steel in the x and y direction respectively, i.e. $A_{st,x} \, / \, (bd)$ and $A_{st,y} \, / \, (bd)$ respectively. The values of ρ_{lx} and ρ_{ly} should be calculated as mean values taking into account a slab width equal to the column width plus 3d each side. Only column steel is taken into account, disregarding the typical BubbleDeck top reinforcement.

f_{ck} = characteristic compressive cylinder strength at 28 days ($= f'_c$)
$v_{min} = 0.035 \, k^{3/2} \, f_{ck}^{1/2}$ EC2 (6.3N)

Accordingly, the maximum allowable shear stress in the hollow areas of a BubbleDeck slab is:

$v_{BD \, Rd,c} = 0.6 \, v_{Rd,c}$

Thus, the control perimeter that defines the extent of the solid zone around the column can be derived from the following expression:

$u_{solid} = V_{max} \, / \, (v_{BD \, Rd,c} \, d)$

Note that the perimeters calculated in accordance with EC2 are the shortest perimeters at a given distance from the face of the column, e.g. for a rectangular section, the control perimeter should be obtained as follows:

$$u = 2\pi a + 2 (bx + by)$$
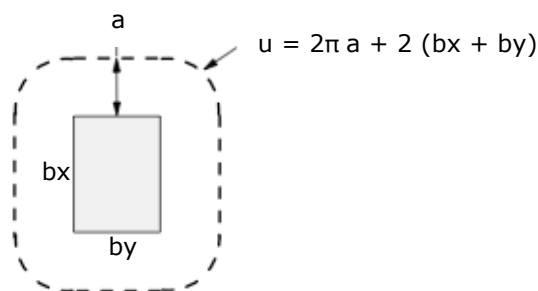
Extent of column tension reinforcement

In order to determine the minimum extent of main tension reinforcement around the columns for which the requirements outlined in the section above are met, a similar perimeter check needs to be carried out, taking into account only the typical top steel of the BubbleDeck elements, without the column steel.

The shear capacity of the hollow slab with only top steel can be calculated using ρ_{lx} and ρ_{ly} for the steel included in the top mat only and a new perimeter calculated.

$v_{BDtyp\ Rd,c} = 0.6\ v_{typ\ Rd,c}$, where

$v_{typ\ Rd,c} = v_{Rd,c}$ using ρ_{lx} and ρ_{ly} for the steel included in the top mat only.

Thus, a perimeter u_{steel} can be determined:

$u_{steel} = V_{max} / (v_{BDtyp\ Rd,c}\ d)$

The perimeter u_{steel} defines a minimum distance from the face of the column to which the column steel must extend. The total length of the reinforcement bars over the columns can then be determined using figure 9.1.3.4 of AS 3600.
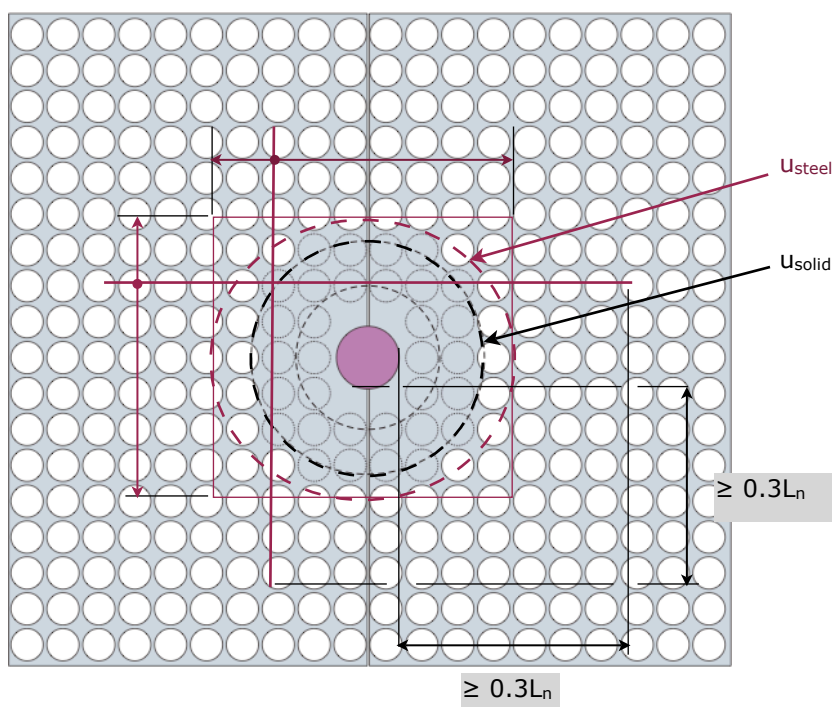
Figure showing perimeters u_{solid} and u_{steel} and extent of column steel

Column shear reinforcement

Column shear reinforcement is calculated in accordance with the guidelines of section 6.4 of EC2, as the provisions of AS 3600 result in complex reinforcement detailing for shallow slabs. The guidelines are applied without alterations as the slab is solid near the columns, and the shear strength is not reduced.

The process for designing any reinforcement that may be required around the columns is iterative. Once the shear check at the perimeter of the column has been satisfied, the shear stress is checked at the basic control perimeter.

The basic control perimeter is taken at a distance 2d from the face of the column, using d as the mean effective depth of the slab $d = (d_x + d_y)/2$, where d_x and d_y are the effective depths in the x and y direction respectively.
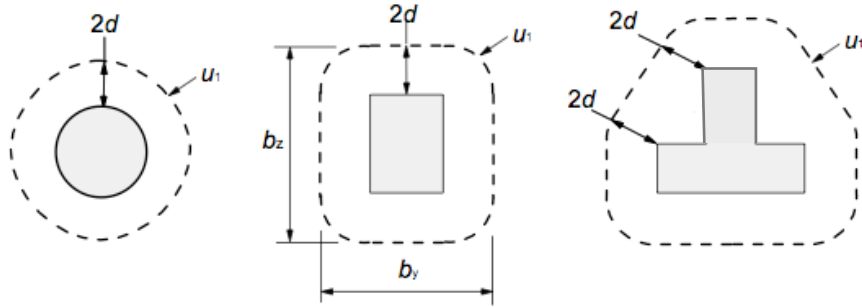
Typical basic control perimeters as per EC2

The shear stress v_{Ed1} at the basic control perimeter u_1 should be checked against the shear strength $v_{Rd,c}$, where:

$v_{Ed1} = \beta\, V_{Ed} / [\, u_1\, d\,]$, and

$v_{Rd,c} = C_{Rd,c}\, k\, (100\, \rho_l\, f_{ck}\,)^{1/3} \geq v_{min}$, using the column tension reinforcement only to determine ρ_l

Punching shear reinforcement is not necessary if:

$v_{Ed1} < v_{Rd,c}$

Where v_{Ed1} exceeds $v_{Rd,c}$ a further perimeter check should be carried out to determine the outer perimeter u_{out} beyond which shear reinforcement is no longer required.

$u_{out} = V_{max} / (v_{Rd,c}\, d)$

Where shear reinforcement is required, it is should be calculated using the following expression:

$v_{Rd,cs} = 0.75\, v_{Rd,c} + 1.5\, (d/s_r)\, A_{sw}\, f_{ywd,ef}\, (\, 1 / (u_1\, d)\,)\, \sin\alpha$, where   EC2 (6.52)

A_{sw} is the minimum area of one perimeter of shear reinforcement around the column

s_r is the radial spacing of perimeters of shear reinforcement and should be limited to 0.75 d

$f_{ywd,ef}$ is the effective design strength of the punching shear reinforcement, according to
       $f_{ywd,ef} = 250 + 0.25d \leq f_{ywd}$

f_{ywd} is the design yield strength of the shear reinforcement $= f_{sy} / 1.15$

f_{sy} is the yield strength of the shear reinforcing steel as per AS 3600

d is the mean effective depth of the slab

α is the angle between the shear reinforcement and the plane of the slab

u_1 is the basic shear perimeter

$v_{Rd,c}$ is the shear strength of the slab without shear reinforcement as calculated in EC2 (6.47)

Once A_{sw} is determined, the reinforcement is placed around the column at successive perimeters spaced at a maximum of 0.75d, up to a distance of 1.5d from the outer perimeter u_{out}. The first perimeter should not be located at a distance greater than 0.3d from the face of the column. The following rules for the shear reinforcement should be observed:
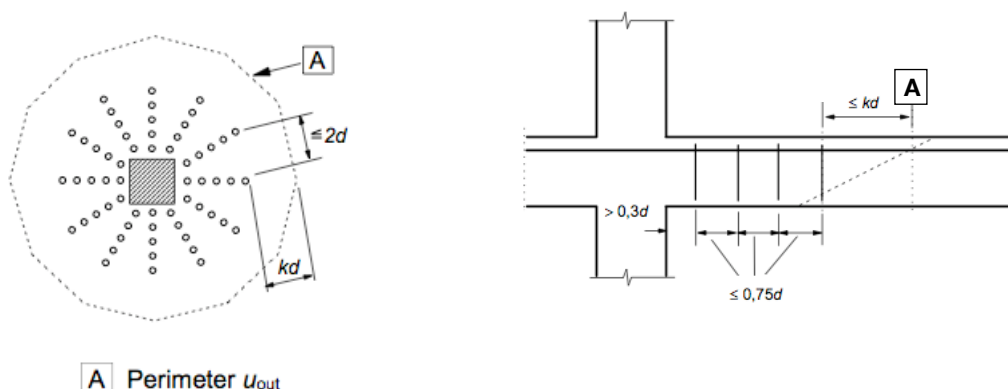

Shear reinforcement detailing requirements

Note that A_{sw} is a minimum area, and additional reinforcement should be added as required in the subsequent perimeters to satisfy the requirement above. Furthermore, at least two perimeters should be provided.

Splice crack width check

The effect of the increased cover to the reinforcement at the splice, when the splice is in a high stress area should be checked for maximum crack width.

An initial analysis of the strains induced by the service moment at the splice can be carried out to determine the minimum area of steel required at the splice. Effectively, the designer can simply check that the maximum strain caused by the service moment at the splice is not greater than the strain caused by the maximum service moment of the element taken at the depth of the splice steel.
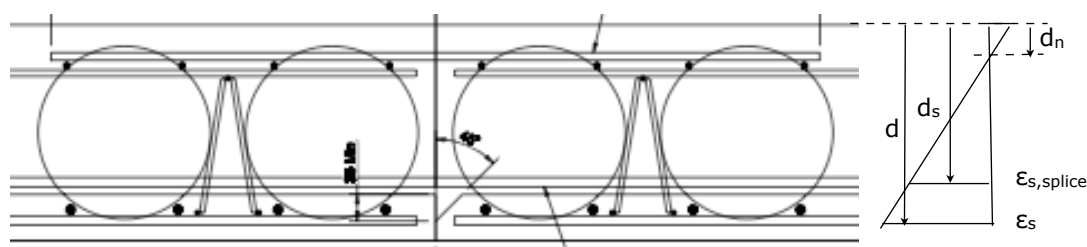
$\varepsilon_{s,splice} < \varepsilon_{s,max} \cdot (d_s - d_n)/ (d - d_n)$, where

$\varepsilon_{s,splice}$	is the strain at the depth of the splice steel at the caused by the service moment at the splice
$\varepsilon_{s,max}$	is the maximum strain of the main steel caused by the service moment
d_s	is the depth to the splice steel
d	is the depth to the main steel
d_n	is the depth of the elastic neutral axis

Alternatively, the maximum crack width can be determined using the expression proposed by Gergely & Lutz (1968) and adopted by the ACI Code and reproduced by *Rangan et al* in *"Concrete Structures", p265.* This should be limited to 0.3mm as recommended by BS 8110.

$w_{max} = 0.0132\ z \le 0.3mm$, where

z   is a factor $z = (\ h\ Ab\ )^{1/3}\ \sigma_{st}\ 10^{-3}$
h   is the cover to the outermost bar - here the cover to the splice bar
A_b is an effective concrete area surrounding each bar $A_b = (\ 2\ b\ t\ ) / (\ No\ bars\ /\ m\ width)$
   b   is 1000 (1m width)
   t   is twice the cover to the bar
σ_{st} is the steel stress under the service moment

References

1. *Eurocode 2 - BS EN 1992-1-1:2004,* published by the British Standards Institution (BSI).

2. *AS 3600-2001,* published by Standards Australia.

3. *Concrete Structures,* Warner, Rangan, Hall and Faulkes published by Longman.

4. *CSIRO report FCO 2645 on BubbleDeck Fire Performance,* dated 24 June 2008.

5. *Assessment of FRL for BubbleDeck floor slabs, Issue 2,* Arup 17 September 2008.

6. *Investigation of BubbleDeck Slabs,* Professor Dr. Ing. Martina Scnellenbach-Held, Darmstadt University.

7. *DIN 1045-1*, *Vol. 1: Building construction; Deutscher Beton-Verein; 2005,* German concrete design code.