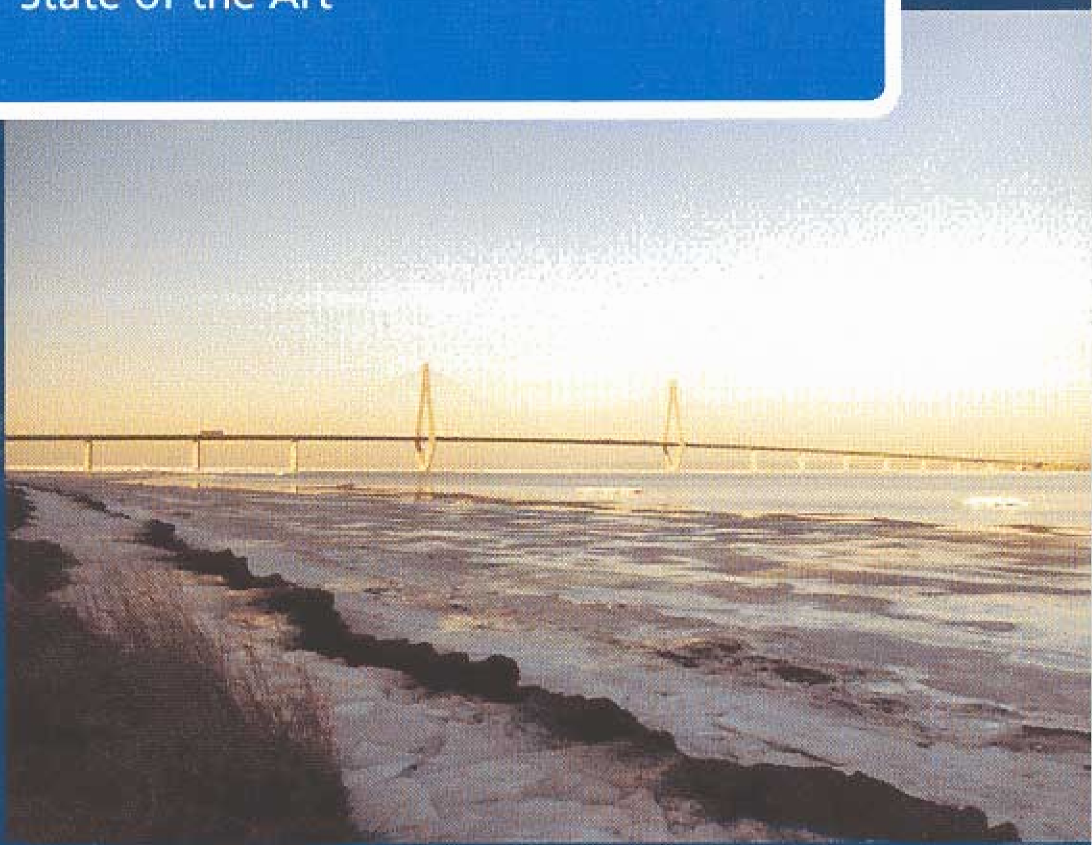
HETEK

Structural Design and Workmanship
State of the Art



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Abstract

This report forms a part of the Danish Road Directorate's research programme called High Performance Concrete - The Contractor's Technology (abbreviated to HETEK). HETEK is divided into eight parts where part no. 5 concerns compaction and structural design.

The State of the Art report regarding structural design and workmanship is based on interviewing a working group consisting of contractors and supervising engineers and study of relevant literature.

Front page photo

The front page photo shows the pylons of the Faroe Bridge between Faroe and Falster , Denmark.
The pylons are partly cast against inclined formwork.

Contents

0. Preface

This programme regarding structural design and workmanship is part of the Danish Road Directorate's research programme, High performance Concrete - The Contractor's Technology (in Danish: Højkvalitetsbeton - Entreprenørens Teknologi abbreviated to HETEK).

High Performance Concrete is concrete with a service life in excess of 100 years in an aggressive environment.

The research programme includes investigations regarding the design of high performance concrete and the execution of the concrete works with reference to obtain the required service life of 100 years.

The research programme is divided into eight parts within the following subjects:

- chloride penetration
- frost resistance
- autogenous shrinkage
- control of early-age cracking
- compaction, structural design and workmanship
- curing (evaporation protection)
- trial casting
- repair of defects

The Danish Road Directorate has invited tenders for this research programme which primarily is financed by the Danish Ministry for Business and Industry - The Commission of Development Contracts.

This programme regarding structural design and workmanship is performed by:

The Danish Concrete Institute represented by

- Find Meyer (Head of the programme)
- Erik Andersen
- Arne Steen Jacobsen
- Bjarne Chr. Jensen
- Alex Kjær
- Flemming Pedersen
- Erik Skettrup

Hans Henrik Orbesen, Phil & Søn, has participated as consultant.

The programme is divided in the following four phases:

Phase 1 Categories of problems, working-note in Danish
Phase 2 State of the Art
Phase 3 Draft Guide in Danish
Phase 4 Guide for structural design and workmanship

This is the State of the Art Report concerning the inexpedient structural details, which are presented in phase 1.

The work has been reviewed by Reidar Kompen, The Norwegian Road Directorate, who is a member of the technical committee associated with HETEK.

1. Introduction

The service life of concrete structures is in focus. Most design engineers are of the opinion that they have always designed the structures with reference to expedient structural design which reduce the risk of defects during execution, and that the codes and standards used are developed in accordance with this.

Nevertheless, it is a fact that errors and defects still occur. Such defects will, locally or in general, reduce the service life and/or increase maintenance expenses.

The occurrence of defects related to the execution may i.a. be caused by:

- incorrect workmanship
- incorrect design
- inexpedient structural design which complicates casting and compaction and consequently increases the risk of defects.

This state of the Art report describes typical inexpedient structural details which complicates casting and compaction. The structural details in question were presented on meetings and obtained by interviewing the following working group:

- Christian Bak, C.G. Jensen
- Niels Coff, Armton/NCC
- Jan Gråbæk, Monberg & Thorsen
- Gunnar Holm, Jord & Beton
- Arne Steen Jacobsen, COWI
- Per Jeppesen, Rasmussen & Schiøtz
- Alex Kjær, Højgaard & Schultz A/S
- Find Meyer, Carl Bro as
- H.H. Orbesen, Phil & Søn
- Flemming Pedersen, COWI
- Erik Skettrup, RAMBØLL

The ascertained problem areas may be divided into:

- Structural geometry
- Cast-in items
- Reinforcement
- Prestressing

The report describes the character of the difficulties in detail.
When possible more expedient alternative structural design is suggested on the basis of relevant literature and on the experience of the working group.

Based on the experience of the working group, the report also describes the most suitable execution method for certain inexpedient structural details which frequently occur.

2. Geometry

Many structures are characterized by attempts to minimize material consumption. This may, however, lead to difficulties during execution of the concrete work. In certain cases the reduced material expenses cannot compensate for the increased cost of labour and temporary structures.

Other complex structures are chosen by the client for architectural reasons. Such structures may be vulnerable. Design should basicly be founded on simple and robust structures and not on slenderness and boldness [Kompen 1994].

Despite careful execution, some structural details may increase the risk of defects and reduced durability. Such structural details are described in this section.

Structures with vertical and horizontal demarcations are preferable, as far as execution is concerned.

2.1 Wall dimensions

Placing of concrete in thin walls with reinforcement of both faces is difficult or sometimes impossible.
The wall should be sufficiently thick, so that a concrete pump hose or casting pipe has free access between the meshes.

Pump hoses are usually 5 or 4 inches.
As a guidance the clearance between the meshes should at least be 150 mm.
If this is not possible, alternative casting methods and/or alternative arrangements of the reinforcement should be taken into consideration in the design phase.

High walls may result in problematic execution of the concrete work. Placing of poker vibrators at the correct level is difficult because of reduced visibility, especially for thin walls. [Frandsen and Schultz 1995].

As a guidance the maximum height, H, for vertical walls without casting joints should not exceed:

H_{max} = 4-6 m for wall thickness less than 0.6 m
H_{max} = 6-8 m for wall thickness greater than 0.6 m

For inclined walls and walls with complex reinforcement the maximum height should be reduced (see section 2.2).

2.2 Inclined surfaces

Concrete surfaces with an inclination less than 90° - see Fig. 1 - can usually be cast as surfaces with vertical demarcation.

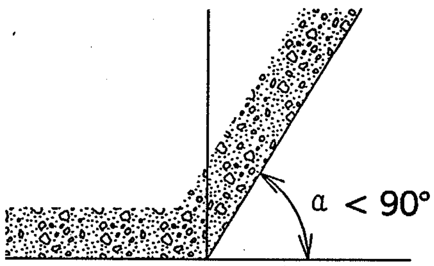


Fig. 1 Concrete surfaces with inclination α < 90°

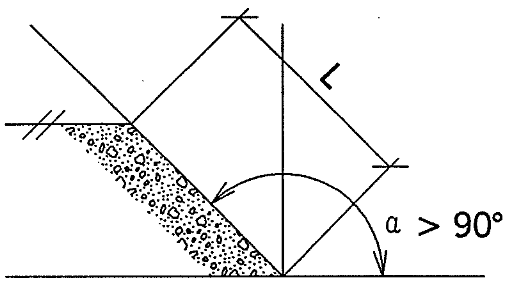


Fig. 2 Concrete surfaces with inclination α > 90°

Surfaces with an inclination greater than 90° - see Fig. 2 - must usually be cast against formwork. Effective vibration underneath the formwork is extremely difficult if the extension of the surface, L, is also significant.

During vibration, air bubbles and bleeding water will rise and follow the formwork. Not all bubbles and bleeding water will escape under normal and recommended poker vibration. [Frandsen and Schultz, 1995]. Surfaces with blow holes are often the result.

The blow holes will locally reduce the thickness of the cover. This may be compensated for by requiring extended cover (10-20 mm).

Inclined walls are in some structures unavoidable. The extent of blow holes can be reduced by the use of form liner. Form liner should be specified for high performance concrete in inclined surfaces where blow holes otherwise would be unavoidable. Form liner is, however, relatively expensive.

Vibration underneath the form must be carried out with special care. This may be done using poker guides placed parallel to the surface, see Fig. 3. This method should ensure sufficient vibration of the surface layer. Vibration directly in the cover cannot usually be recommended. [Frandsen and Schultz, 1993].

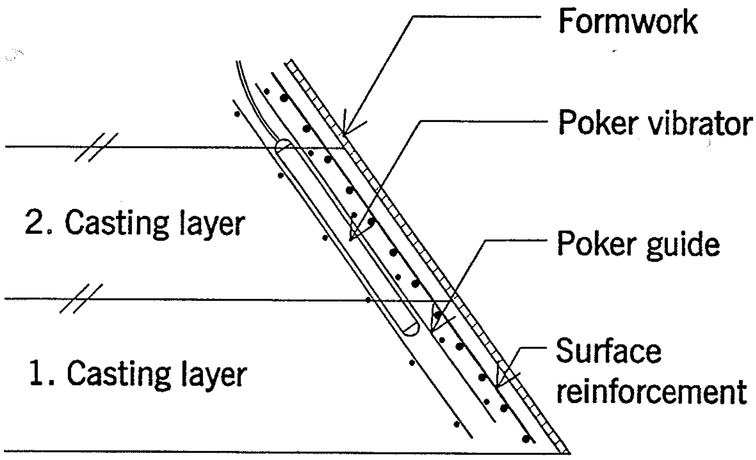


Fig. 3 Vibration underneath inclined formwork.

When α (see Fig. 2) is almost 180° the concrete surface cannot be cast against an unbroken formwork because, in this case, vibrating underneath the form is impossible. Such slightly inclined surfaces may be cast using form units which are placed successively during the casting. It is also possible to use formwork which only partially covers the surface, thus allowing the airbubbles to escape. Alternatively the surfaces could be cast without forms which, however, could possibility lead to deformations during vibration, screeding and finishing.

When possible surfaces should be designed horizontal with only a small slope to facilitate water run-off.
A standard design for foundation slabs is shown on Fig 4a. The design in Fig. 4b which is preferable for the execution [Kompen 1994] will result in a higher concrete consumption.

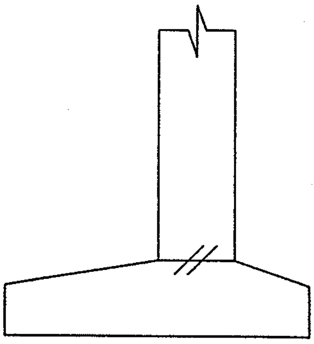


Fig. 4a. Foundation slab
Standard design

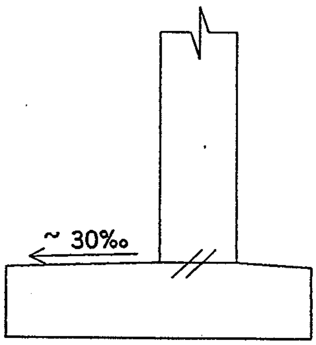


Fig. 4b. Foundation slab
Almost horizontal surface

2.3 Drainage Profiles

When the necessary room for a one-sided slope is not available, the structural design for drainage of deck slabs is often based on two-sided slopes (see Fig. 5a). Usually casting is required to be carried out without any horizontal casting joints. Finishing and screeding of the concrete surface is time consuming and difficult. The execution will often lead to significant variance in reinforcement cover as well as formation of early age cracking due to late placing of evaporation protection. Therefore from the contractors' point of view introduction of a horizontal casting joint (Fig. 5b) is preferable.

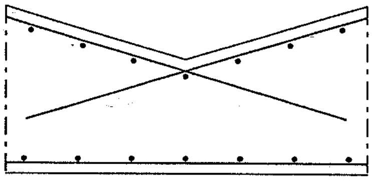


Fig. 5a Deck slab two-sided slope. without casting joint

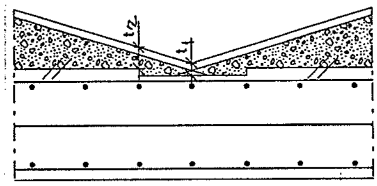


Fig. 5b Deck slab two-sided slope with casting joint

Experience shows, however, that the layer above the casting joint has a tendency to peel, resulting in increased deterioration of the structure below the casting joint.

2.4 Casting joints

Casting joints between foundation slabs and walls are often placed some distance above the top of the foundation slab. This implies a risk of movement of the concrete in the small part of the wall during vibration - see Fig. 6a.
The movement may be counteracted by placing expanded metal and/or a skirt as shown on Fig. 6a. Expanded metal is rather weak and flexible and should only be used if the pressure caused by the concrete and the vibration is low. A high pressure may introduce cracks.
A preferable structural design is, however, the placement of the casting joint at a level corresponding to the upper surface of the foundation slab.

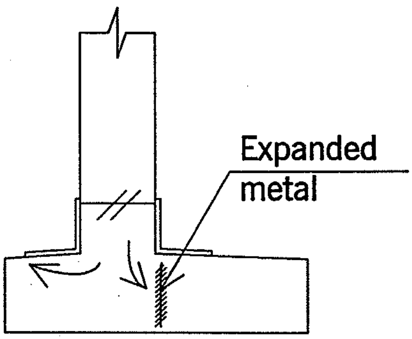


Fig. 6a. Casting joint placed some distance above the top of the foundation slab.

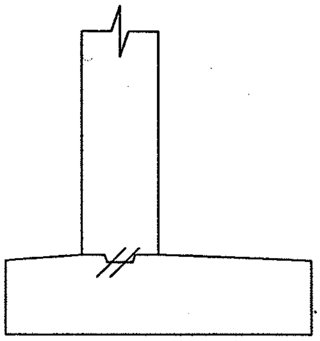


Fig. 6b. Casting joint placed at the top of the foundation slab

Casting joints in the walls direction should also preferably be horizontal.
If the depth of foundation varies considerably, it is advantageous to change the level discontinuously as shown Fig. 7b.

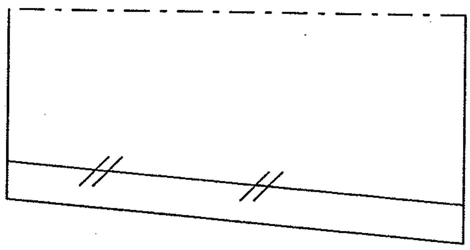


Fig. 7a Longitudinal continuous variation of foundation depth

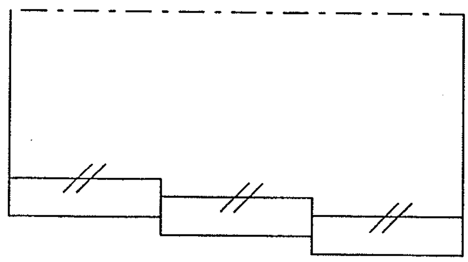


Fig. 7b. Longitudinal discontinuous variation of foundation depth

2.5 Box-outs

Box-outs generally lead to difficulties concerning placing and vibration of the concrete below the box-out. The difficulties are significant when the box-outs are of a large horizontal extension, and when there is only a small distance between the casting joint and the lower level of the box-out.
To facilitate the execution of box-outs in walls the distance between the casting joint and the lower level of the box-out should be at least of the same magnitude as half the length of the box-out. Alternatively, the box-out could be extended, starting from the casting joint, so that no concrete at all has to be placed below the box-out.
The structural design should respect these circumstances.

Fig. 8a shows a box-out with a lower level too close to the casting joint. If possible, the vertical distance from the casting joint to the box-out should be increased to 600 mm.
Fig. 8b shows an alternative design with the casting joint placed at the upper level of the foundation slab - re. section 2.4. The change increases the distance between the casting joint and the box-out to 500 mm, which is half the length of the box-out.

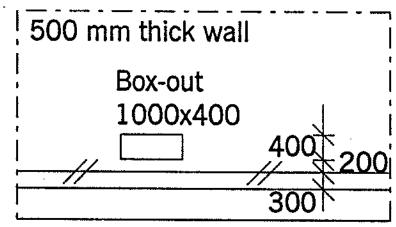


Fig. 8a. Box-out in a wall placed 200 mm above the casting joint

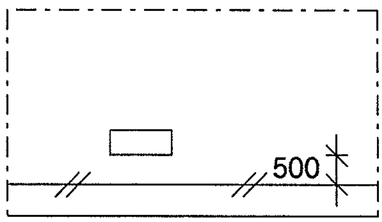


Fig. 8b. Box-out in the same wall but placed 500 mm above the casting joint

The best possible execution of a number of closely placed box-outs is obtained when the casting is carried out systematically from one side - ensuring complete compaction below the box-out - before casting from the other side is initiated.

The shape of the box-out also has influence on the result of the execution. Circular, oval and rhombus shaped box-outs are better than square and rectangular shaped. The arrangement of reinforcement is, however, more complex for the first mentioned. If possible, square and rectangular box-outs should be placed diagonally as shown in Fig. 9. This solution will also facilitate the casting around pipes passing through the box-out.

Execution of box-outs with large horizontal extension may be performed with a pipe passing though the box-out for placing and vibration of the concrete below the box-out (see Fig. 9). The concrete in the pipe has to be removed after stripping, and the surfaces - if necessary - sand blasted. To minimize the number of blow holes in the lower surface, ø 5-10 mm holes can be drilled in the bottom of the box-out and/or form liner can be applied.

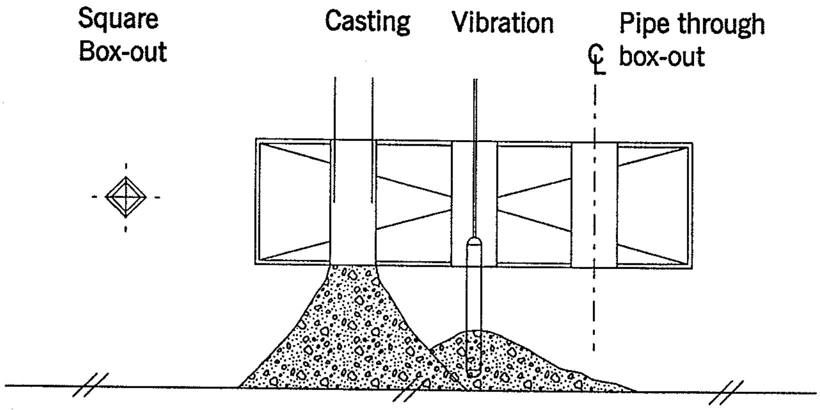


Fig. 9. Casting and vibration of concrete below a box-out with large horizontal extension and placing of square box-outs.

Sometimes a waterstop is required in the middle of the wall all the way round the box-out. In this case the execution method based on centrally placed pipes as shown in Fig. 9 is impossible. Waterproofing should therefore be ensured in another way.

Most designs require - often in a note on a drawing - that additional reinforcement must be placed around the box-outs. Such additional reinforcement will further complicate execution. To ensure accomplishment in accordance with the execution method outlined in Fig. 9 the additional reinforcement should be placed in the surface of the wall parallel to the ordinary reinforcement [Kompen, 1993].

If the box-out will later have to be closed, continuity of reinforcement can be obtained by the use of reinforcement couplers.

2.6 Recesses

Recesses as shown in Fig. 10 are usually carried out by means of a box-out.
The horizontal lower surface of the recess will often be subject to blow holes caused by rising air bubbles and bleeding water. The extent of blow holes may be reduced by drilling holes in the box-out and/or by applying form liner - see section 2.5.

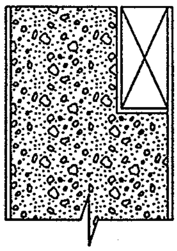


Fig. 10. Recess

2.7 Chamfering

During the structural design process, it should be remembered that chamfers placed in the formwork reduce the clearance. The minimum clearance for walls should be 150 mm - see also section 2.1.

Large chamfers can result in reduced cover to reinforcement placed behind the chamfer.

2.8 Drip caps

Concerning the structural design of drip caps, it should be remembered that the groove is formed by placing moulding.

The mouldings are nailed to the formwork below, and it should be noted that thin mouldings have a tendency to twist and bend during casting even when the distance between the nails is reduced. This may be improved if the groove design is deeper and wider using for instance trapezoidal mouldings with thickness 19-25 mm. Such mouldings have sufficient rigidity.
The arrangement of the reinforcement and cover around the groove must be considered carefully during the design phase - see also section 2.9.

2.9 Trapezoidal grooves

Casting joints are sometimes required to be carried out with trapezoidal mouldings. The dimensions of the moulding should be sufficient to prevent twisting and bending during casting - see section 2.8.
To ensure the required minimum cover the moulding may be placed as shown in Fig. 11.

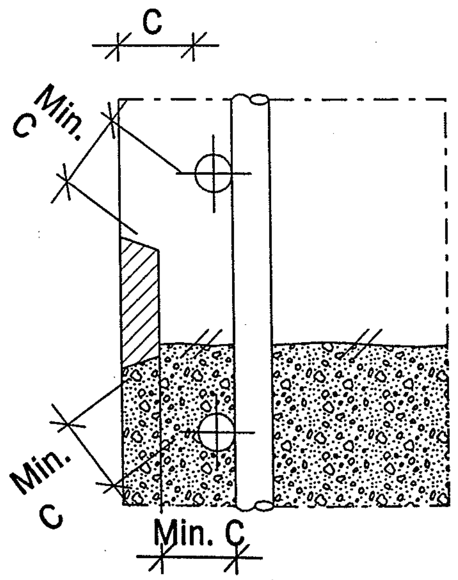


Fig. 11. Structural design for trapezoidal groove. C = concrete cover.

The design shown in Fig. 11 can only ensure sufficient cover if:

- the outer reinforcement is parallel to the groove
- the distances from the moulding to the nearest reinforcement bars are larger than the required cover

If these assumptions cannot be conformed with, the cover could be increased. Otherwise a local reduction of the cover by the trapezoidal groove has to be accepted, e.g. by introducing a surface protection of the groove.

3. Cast-in items

To ensure the best possible workmanship, cast-in items should not protrude from the concrete surface in which they are cast. If the geometry prevents compliance with this general rule it is, from a constructional point of view, advantageous to base the design on a box-out. The item can then be cast in after the formwork has been removed.

Cast-in items with inclined lower surfaces will ensure the best possible encasement as far as air bubble accumulations are concerned.

3.1 Edge iron

Structures exposed to impact forces, which may strike off edges, are often strengthened by casting-in edge irons.
The design of edge irons placed on top of walls shall respect the required minimum clearance 150 mm - see section 2.1.

3.2 Cavity tubes

Some structures require use of cavity tubes in deck slabs or beams in order to reduce the dead load. During execution there is a risk that the pressure from the wet concrete may lead to deformation of the cavity tubes and, in the worst case, the buoyancy may result in incorrect positioning of the tubes.
The tapered parts at the ends of the cavity tubes are especially difficult to handle during casting and incorrect profile grade and pondings are at risk.

To ensure the best possible execution, the following measures should be respected:

- The fastening of the cavity pipes to the formwork must be sufficient to resist the buoyancy forces.

- Special care concerning fastening of the tapered parts of the ends of the cavity tubes must be taken.

- The thickness of cavity pipes must be sufficient to resist the loads during casting without buckling and deformation.

It is important during the casting to ensure that the concrete has filled the area below the cavity pipe completely. The best method is to cast systematically from one side of the cross section - ensuring complete grouting - before casting from the other side of the cross section.

In the longitudinal direction execution may be performed by one of the following techniques:

1. Casting horizontal layers.
   If the casting is carried out with horizontal concrete layers, it may be necessary temporarily to stop casting when the concrete surface has reached a height corresponding with the centre line of the cavity tubes. The buoyancy will be reduced if the casting is not continued before the lower parts of the concrete layers have stiffened. The workability of the upper layer must however be sufficient to ensure effective vibration - or in other words the casting stop must not be too long.

2. Casting inclined layers.
   Some contractors prefer a casting technique based on inclined casting layers. The extent of the casting layers should cover the total cross section - see Fig. 12.

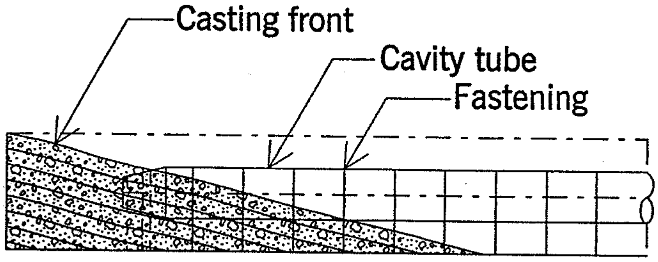


Fig. 12. Cavity tubes. Casting with inclined casting layers. Longitudinal section.

Using this method the concrete of the initial casting layers will be so stiff that there is no buoyancy from this concrete. The advantages of this method are increased by using thin casting layers and relatively slow casting.

The above mentioned difficulties in execution of cross sections with cavity tubes are further increased if the reinforcement percentage is high and/or if prestressing cables are present.
Cavity tubes should therefore be carefully considered at the design stage.

3.3 Cooling pipes

Cooling pipes in walls should be placed in the centre where the temperature is highest during hardening. Depending on the wall thickness and reinforcement arrangement it should be considered whether it is advantageous for the casting to place the cooling pipes vertically or horizontally.

It should be considered whether the cooling can be established without cooling pipes e.g. using cooled aggregates and/or cold water for the concrete production.

The structural design usually includes establishment of casting joints. In the design phase it is important to form an idea of the structural elements which have to be cooled in order to comply with the temperature requirements for structural elements separated by casting joints. The aim should be to reduce the number of structural elements where cooling is necessary.

4. Reinforcement

The reinforcement shall be arranged in such a way that proper casting of the concrete is possible.

4.1 Spacing of bars
[Eurocode No. 2] cl. 5.2.1.1 and 6.3.3.5 defines i.a.:

1. The spacing of bars shall be such that the concrete can be placed and compacted satisfactorily and that the development of adequate bond is assured.

2. The maximum aggregate size, d_g, should be chosen to permit adequate compaction of the concrete round the bars.

3. The clear distance (horizontal and vertical) between individual parallel bars or horizontal layers of parallel bars should be not less than the maximum bar diameter or 20 mm. In addition where $d_g > 32$ mm, these distances should be not less than $d_g + 5$ mm.

4. Where bars are positioned in separate horizontal layers, the bars in each layer should be located vertically above each other and the space between the resulting columns of bars should permit the passage of an internal vibrator.

5. In areas of congested reinforcement, sufficient spacing of the bars shall be provided to allow proper compaction of the concrete.

For clarification the following should be emphasized:

ad 1) and 4):
If the structural height is above the permitted free fall of concrete (usually 1 m) the reinforcement should be arranged to allow for the insertion of concrete hoses.
The required openings should be not less than 150 x 150 mm - see Fig. 13. The maximum distance between the openings depends on the workability of the concrete and should usually not exceed 2 m.

ad 1). 4) and 5):
The required openings for the insertion of poker vibrators should be not less than d + 40 mm where d is the diameter of the poker vibrator - see Fig. 13.
The maximum distance between the openings depends on the complexity of the structure - including the reinforcement - and the diameter of the chosen poker vibrator.

The principles for determination of maximum insertion distance and consequently the distance between openings are described in "Guide for poker vibration" [Frandsen, J. and Schultz, K.I.].

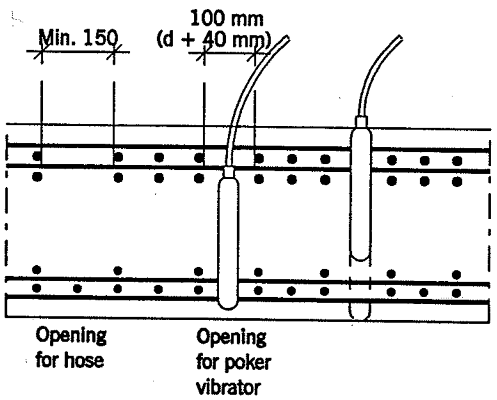
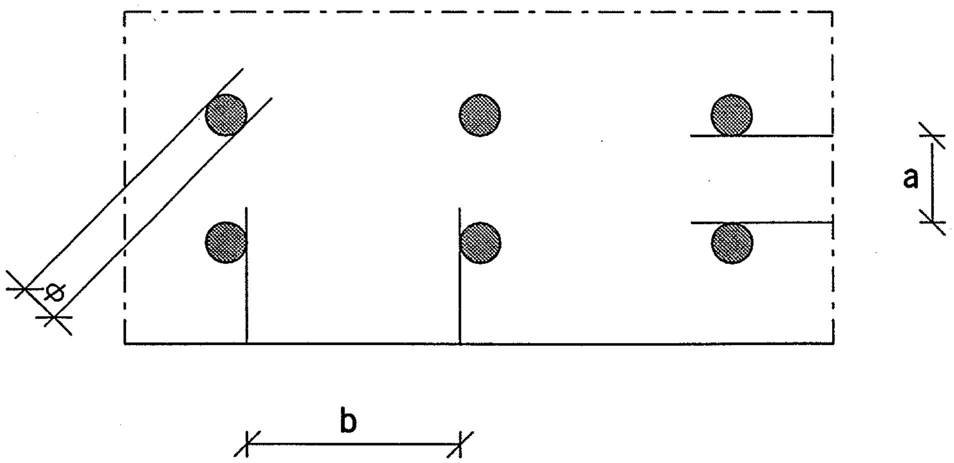


Fig. 13. Openings for hose and poker vibrator

ad 2):
The maximum aggregate size, d_g, is usually defined prior to the detailed design of the reinforcement of the specific structural elements.

ad 3):
The Danish code of practise DS 411, defines the minimum clear distance between individual parallel bars as: two times the maximum bar diameter or d_g + 10 mm.

The minimum clear distance between horizontal layer of parallel bars is defined as: The maximum bar diameter or d_g. The difference between Eurocode and The Danish code of practice is shown on Fig. 14.



a.	DS 411	: min. ø or d_g	
	Eurocode 2	: min. ø or d_g mm	for $d_g < 32$ mm
		min. $d_g + 5$ mm	for $d_g > 32$ mm
b.	DS 411	: min. 2 ø or $d_g + 10$ mm	
	Eurocode 2	: min. ø or 20 mm	for $d_g < 32$ mm
		min. $d_g + 5$ mm	for $d_g > 32$ mm

Fig. 14. Minimum clear distance between individual parallel bars and horizontal layers of parallel bars.

It can be seen in Fig. 14, that the Danish code of practice requires wider spacing between parallel bars, b, than the Eurocode.
The distance a, between horizontal layers is in practice the same because the maximum aggregate size, d_g, is usually less than or equal to 32 mm.

A wide spacing, b, is important for a proper casting and compaction. The distance, a, between horizontal layers is of less importance.

To increase the spacing, b, the following simple rules should be implemented at the design stage:

- large bar diameters are preferable.
- bundled reinforcement is preferable.
- two horizontal layers are preferred to one layer.

However, for fulfilment of the crack width requirements, these remedies will result in higher steel quantities.

4.2 Laps

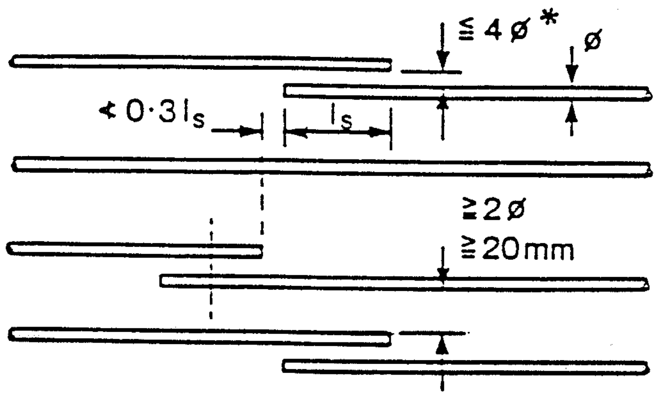
Eurocode No. 2 cl. 5.2.1.1 and 5.2.4.1.1 defines i.a.:

1. Lapped bars may touch one another within the lap length.

2. Laps between bars should as far as possible be staggered.

3. Laps at any one section should as far as possible be arranged symmetrically and parallel to the outer face of the member.

4. The clear space between the two lapped bars (in both vertical and horizontal plane) in a joint should comply with the values indicated in Fig. 15.



* otherwise the lap length shall be increased by the amount by which the clear space exceeds 4ø.

Fig. 15. Adjacent laps

A wide spacing between lapped bars is important for a proper casting and compaction. The spacing may be increased if:

- large bar diameters are used.
- bundled reinforcement is used.
- two layers of reinforcement is used instead of one.

4.3 Starter bars

The observations in section 4.2 concerning laps are also valid for starter bars. For complex reinforcement it may be necessary to require the use of screwcouplers or sleeves in order to ensure proper concreting and effective compaction.

5. Prestressing

Design of structures with prestressing tendons should respect the guidelines given in the Codes of Practice.

The Danish Code of Practice DS 411 specifies the minimum clear horizontal and vertical distances between prestressing tendons.
The detailed description can be found in the Danish Code of Practice DS 411, paragraph 6.4.2.2.

The Eurocode No. 2 defines i.a.:

- Placing of the tendons shall be carried out in compliance with the criteria related to the ease with which the concrete can be cast.

At the anchorage zones the accumulation of reinforcement, bond head anchorage etc. is often significant.
To ensure sufficient insertion possibilities for poker vibration it may sometimes be necessary at the design stage to perform large scale drawings of these congested areas.

6. Recommendations

Through interviews and literature studies, typical inexpedient structural details are described.
Some of the problems have not previously been treated systematically.

This is entirely or partly the case for:

- Structural geometry
- Cast-in items

This report deals with structural design which, concerning casting and compaction, is more or less appropriate. Furthermore the report includes the contractor's possibilities as far as execution methods are concerned.

It is recommended to produce drawings which illustrate good and poor structural design in order to clarify the above mentioned details. The drawings should be included in the final guide. The guide should include proposals for remedial corrections for the design and for the execution.

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