APPENDIX 1- FORMWORK BASICS

Definitions

Let us start by a straightforward definition of what is generally understood by formwork.

FORMWORK is a mould or open box into which fresh concrete is poured and compacted. The purpose of formwork is to safely support the reinforced concrete until it has reached adequate strength.

Formwork can be a temporary structure or a permanent mold. Usually Formwork is erected quickly, highly loaded for a few hours during the concrete placement, and disassembled when the concrete has hardened enough to hold its own weight and any other loads it has been designed to carry.

Formwork system can be generally classified as Vertical Systems (wall and column) and Horizontal Systems (slab and beam). The possibility to design and build formwork for other applications exists. The material serving as the contact face of forms is known as sheathing and it is used in both the vertical and horizontal systems. Form-facing material should be steel, glass-fibre-reinforced plastic, or other approved non-absorptive panel materials. Elements support the sheathing firmly in place and together the constitute system is the formwork.

The operation of removing the formwork is known as stripping. Stripped formwork can be reused. Reusable forms are known as panel forms and non-usable are called stationary forms.

FALSEWORK. Falsework is any temporary structure used to support the forms for concrete. Falsework supports the forms until the concrete can support itself. It must be strong enough to support the weight of the forms, the fresh concrete and any construction equipment and workers. Falsework may be equipped with hydraulic jacks, wedges and other approved devices.

SHORING AND PRESHORING. Shoring is a system of vertical or inclined support members designed to carry the weight of the formwork, concrete, and construction loads above. Shoring systems may be made of wood, metal posts or various patented members Shores must be correctly installed and wedged securely so that each carries its share of load.

Preshores, also known as backshoring, is used when the formwork is removed from the freshly placed concrete before the concrete has achieved sufficient strength to support itself. They should not be removed until the slab or beam has sufficient strength to support all loads that will be applied to it.

The same equipment is used for shoring, reshoring, and preshoring. It is the use of the equipment that identifies its function. No shores should be removed without proper authorization.

SCAFFOLDING. Scaffolding is a system consisting of tubular steel frames and wooden boards to provide access to operators and support for tools and materials during construction at a certain height. For large concrete structures, heavy-duty scaffolding is often adapted to double as shoring.

BRACING. Bracing are supplementary formwork members designed to resist lateral loads and to prevent instability, which is why they are commonly referred to as lateral bracing due to their purpose. Adequate bracing is important to stability and safety and should also be provided to resist wind and the various lateral forces that may occur during construction.

FORM ACCESSORIES

Form ties

When concrete is placed in wall formwork, the pressure exerted by the fresh concrete tends to force the opposite sides of the formwork apart. In order to secure concrete forms against the lateral pressure of unhardened concrete, an economic solution is to use a tensile unit connecting opposite sides of the form called concrete form tie (they are also referred to as form clamps, coil ties, rod clamps, snap ties, etc.).

Form ties collect the force exerted by the concrete firstly onto the face material of the form and then to the walling to distribute the force. Fibre-reinforced plastic ties are also available.

Ties are ready-made units with safe load ratings ranging from 400 kg to more than 20,000 kg and have an internal tension unit and an external holding device.

Tie systems fall in two categories: non-recoverable ties and recoverable ties

Non-recoverable ties

1) Snap tie
2) Mild Steel Ties
3) Coil Ties
4) High Tensile Ties

Recoverable Ties

After concrete is placed the ties are removed and a hole is left behind of it. Given that Windcrete must be watertight, recoverable ties are not suitable and will not be discussed any further. Non-recoverable ties will be used instead.

Form anchors

Form anchors are devices used to secure formwork to previously placed concrete of adequate strength. The devices normally are embedded in the concrete during placement.

Side form spacers

A side form spacer is a device that maintains the desired distance between a vertical form and reinforcing bars. Both factory-made and job-site fabricated devices have been successfully used.

IMPORTANCE OF FORMWORK

Formwork for concrete structures has a significant impact on the cost, time, and quality of the completed project. Economy is a major concern since formwork costs can constitute up to 60 percent of the total cost of concrete work in a project (Tokyo Institute of Technology, 2005; K.M Nemati). Usually the construction of formwork takes time and involves expenditure of up to 20 to 25% of the cost of the structure, or even more for singular projects. For some structures, the cost of formwork exceeds the cost of the concrete and steel combined.

Each structure is unique, and for this reason the formwork must be designed and fabricated based on the specific requirements of each project. In this part, the basic the principles and techniques for design of formwork for concrete structures are presented.

Thus, an accurate formwork design is important to construct Windcrete as it will be a major cost of the concrete structure to be built. Because of the impact of formwork on costs of concrete structures, planning and designing the formwork system should be seen as an integral part of the process of designing and constructing the concrete towers. Optimizing formwork is a unique chance for Windcrete to cut down costs for tower production in a radical way.

MATERIAL OF FORMWORK

The appropriate material for the forms should be chosen. The choice of material of the form affects the quality of surface finish of the concrete. The main materials are plywood, timber and steel. Together with the size of the forms, the choice of material has direct impact on the weight of forms and on the equipment required to handle the forms.

Forms frequently involve the use of two or more materials. Materials used for formwork for concrete structures include:

- Lumber
- Plywood
- Steel
- Aluminium
- Magnesium
- Plastics

Other materials are used for formwork like hardboard, fiberglass, Plaster of Paris, corrugated boxes etc.

Additional materials include nails, bolts, form ties, braces anchors. Some of these accessories will be described further in this chapter.

Form materials should possess the following properties:

- Adequate strength to withstand construction loads, handling and reuse.
- Adequate rigidity to maintain the designed shape of the concrete.
- Surface smoothness, where required.
- Economy, considering initial cost and number of reuses.

RELATION BETWEEN DESIGN PROCESS AND CONSTRUCTION PROCESS

A first priority in designing for economy is selecting the structural system that offers the lowest overall cost while meeting load requirements. Normally, this cannot be achieved only by focusing on minimizing the amount of permanent material. Too often the designers of concrete structures devote considerable time in minimizing the amount of concrete and steel for a structure without devoting adequate attention to the impact of the formwork that must be constructed to form the concrete (Garold D. Oberlender, 2010). Two or more structural alternatives will meet the design objective equally well. However, one alternative may be significantly less expensive to build.

Thus, the design process will have a major impact on the construction process and both need to be addressed simultaneously. “Design for construction” principle clearly illustrates the need of a coupled approach, taking into account constructability even at the earliest design stage.

The following example shows the total cost of a hypothetical building for 2 different design outlook. It has been selected from *Concrete Buildings, New Formwork Perspectives* (Ceco Industries, 1985) and aims at showing what can be gained by designing according to the” Design for construction” principle. The 2 different design approaches are:

-Design A, where the priority was permanent material economy and
-Design B, where the same project is redesigned to accelerate the entire construction process by sizing structural members that are compatible with the standard size dimensions of lumber, which allows for easier fabrication of forms.

The results of the total cost of this hypothetical building according to the design approach that has been followed are presented in

Table 1 Comparaison of design A & design B. Source: (Ceco Industries, 1985)

Cost Item	Emphasis on Permanent Material, Design A		Emphasis on Constructability, Design B		Percent Increase (Decrease)
FORMWORK Temporary material, labor, and equipment to make, erect, and remove forms	\$5.25/ft^2	51%	\$3.50/ ft^2	39%	(33)
CONCRETE Permanent material and labour for placing and finishing concrete	\$2.85/ ft^2	27%	\$3.00/ ft^2	33%	5
REINFORCING STEEL Materials, accessories, and labour for installation of reinforcing steel	\$2.25/ ft^2	22%	\$2.50/ ft^2	28%	11
Total cost	\$10.35/ ft^2	100%	\$9.00/ ft^2	100%	(13)

For Design A, permanent materials are considered to be concrete and reinforcing steel. The total concrete structural frame cost is \$10.35/ ft^2. For Design B, the emphasis is shifted to constructability, rather than permanent materials savings. The time has been reduced, with a resultant reduction in the labour cost required to fabricate, erect, and remove the forms. Note that for Design B the cost of permanent materials has actually increased, compared to the cost of permanent materials required for Design A. However, the increase in permanent materials has been more than offset by the impact of constructability, that is, how easy it is to build the structure. The result is lowering the cost from \$10.35/ ft^2 to \$9.00/ ft^2, a 13% savings in cost.

What can be drawn from the previous example is the close link between constructability and designing an economic formwork. Constructability, that is, making structural frames faster, simpler, and less costly to build, makes room for an important opportunity to reduce costs and must begin in the earliest phase of the design effort.

ECONOMY OF FORMWORK FOR WINDCRETE

The question rises, can it be said that the structural design of Windcrete was done according to "Designed for construction" principle? Is Windcrete in line with the notion of constructability?

As mentioned, constructability of a particular design is closely linked to its economic feasibility. Economy in formwork begins with the design of a structure and continues through the selection of form materials, erection, stripping and care of forms between reuses.
The design of formwork for Windcrete should integrate constructability into the project by allowing three basic concepts: design repetition, dimensional standards, and dimensional consistency. These three concepts are all the more important when planning for a serial production.

Design Repetition
The construction of Windcrete will be more efficient if it is performed on a repetitive basis. By designing the construction procedure in an assembly line, efficiency and economy by repetition can be achieved. This is particularly applicable to large structures with almost constant cross-section as is the case of Windcrete. As the bottom part of the tower is made up of 120m of constant circular section, repeating the same casting operation should be possible which represents an advantage. What can be observed from the structural design of Windcrete should is that the construction procedure should use repetition to its advantage. It is also important to point out the benefits of providing repetition for the workers…

Dimensional Standards
This second concept refers to the use of standard formwork products and is particularly relevant when using wood in formwork, especially lumber and plywood. It is recommended to make use of standard nominal dimensions when designing formwork to match them to patented standard size forms offered by manufacturers.

However, in the case of Windcrete one must accept almost at once that the forms to be used will be specially fabricated for Windcrete. Due to the large dimensions of the concrete towers and the specific requirements of the construction process, the forms will be constructed in factory conditions to suit the needs of the project. Additionally, wood does not appear as the first choice of formwork material for a serial production, instead metal forms may be preferred as they offer a maximum number of re-uses. Nonetheless, even if readily existing commercial forms are impracticable, the principle of Dimensional Standards should be present when manufacturing the circular formwork for Windcrete. By carefully selecting a uniform form design, with optimal weight and dimension, one could define a dimensional standard specific to Windcrete. By designing forms as homogenous as possible, cost reductions can be achieved in fabrication of the forms, as a standard design that can be repeated is easier to produce. A standard form is also cheaper to transport to site as it could allow to standardise required vehicles and transportation process. Form handling operations would also benefit from a uniform form design as a single type of lifting equipment could be employed.

In practice using a single form design for the entire construction of Windcrete will not be possible since the geometry of the tower is not constant. However, under all circumstances, an effort should be made to keep the number of different forms to a minimum to take advantage of the concept of dimensional standards.

Dimensional Consistency

For concrete structures, consistency and simplicity yield savings, whereas complexity increases cost (XX). This concept recommends the designer to take advantage of less expensive structural alternatives, like increasing the concrete strength or the amount of reinforcement, rather than changing the size of the structural member and consequently the size of the formwork. According to this concept, it is usually more cost efficient to vary concrete properties or the amount of reinforcement to accommodate differing loads than to vary the size of the formwork.

This concept complements the previous and urges simplifying the structural member design as much as possible for a simplified -and therefore- cheaper construction procedure. Once again, the cylindrical structural design Windcrete

We are now in position to briefly answer the question: *Is Windcrete in line with the notion of constructability?*

In terms of formwork, yes.

As can be observed from the current geometry of the tower, Windcrete already integrates constructability in its design. In fact, Windcrete satisfies the design concept of Dimensional Consistency by maintaining a similar cross-section when possible. The optimized shape that can be subdivided in 3… accommodates the possibility to define some dimensional standards of the forms to be used, which could considerably favour the overall costs related to form fabrication, form handling and erecting by standardizing equipment present at the worksite. What can also be derived is that the construction procedure must include repetition at its core. By integrating repetition of activities in the construction process a cost-efficient and convenient solution can be reached and Windcrete's constructability in terms of formwork can be taken advantage.

PROPERTIES OF GOOD FORMWORK

Several aspects should be kept in mind when designing correctly for formwork. First the most important aspects to consider are presented. Then each of these aspects will be further developed according to the specific requirements of Windcrete. The most important aspects to consider for the design of forms are:

Quality

The forms and other structures are designed and built accurately so that the desired shape, size, alignment and finish of the cast-concrete is achieved in terms of dimension and strength. The forms must, Forms must be sufficiently rigid under the construction loads to maintain the designed shape within permissible deflections and tolerance limits. Forms must withstand handling and reuse without losing their dimensional integrity. To avoid rusting, forms surfaces should be oiled with an appropriate releasing agent in between uses.

Economy of Formwork

Economy is a major concern since formwork costs can constitute up to 60 percent of the total cost of concrete work in a project (Tokyo Institute of Technology, 2005; K.M Nemati). Economy involves many factors, including the cost of materials; the cost of labour in making, erecting, and removing the forms, and the cost of equipment required to handle the forms. The most economical design must consider the total process, including material, time, labour, and equipment required to fabricate, erect, and remove formwork as well as the permanent materials of concrete and steel.

Safety of Formwork

The failure of formwork is a major concern of all parties involved in a construction project. The forms must be designed adequately by the designer to sustain all the loads that appear during construction whilst keeping in mind the specific job conditions that exist at each jobsite. It is the responsibility of the workers at the jobsite to fabricate and erect the formwork in accordance with the design.

LOADS ON FORMWORK

When it comes to loads, formwork should be seen as a typical structure subject to loads no different from those applied on regular structures. These are:

- dead loads – permanent; including self-weight, floor covering, suspended ceiling, partitions, etc.;
- live loads – not permanent; the location is not fixed, equipment, occupants for buildings, etc.
- wind load (exerts a pressure or suction on the exterior of a structure);
- earthquake loads (the effects of ground motion are simulated by a system of horizontal forces);
- snow load (varies with geographical location and drift).

However, assuming the working site is relatively sheltered and not located in a seismic region, one may focus on the first two. Loads on formwork can be further divided in horizontal and vertical loads.

Horizontal loads - Lateral Pressure of Fresh Concrete

Lateral Pressure of Fresh Concrete is the main design load for formwork. The freshly placed concrete behaves temporarily like a fluid, producing a hydrostatic pressure that acts laterally on vertical forms. The effective lateral pressure –a modified hydrostatic pressure– is shown below.

The pressure imposed by concrete on a wall form is a function of the following primary factors:

1) Density of concrete.
2) Temperature (T) of the concrete mix at the time of placing (degree Fahrenheit).
3) Rate (R) of concrete placing (feet of height per hour).
4) Height (h) of concrete placement (in feet).
5) Use of retardant admixtures.
6) Vibration.

Note that with slower rate of placing, concrete at the bottom of the form begins to harden and lateral pressure is reduced to less than full fluid pressure by the time concreting is completed in the upper parts of the form.

Note that fresh concrete loads, ruling formwork design, vary if you consider the forms in upright position or placed in horizontal.

Horizontal Loads

Fresh concrete exerts a lateral pressure on vertical form surfaces which has to be asseessed to design forms. In the simplest theory, fresh concrete acts as a fluid exerting pressure equally in all directions at whatever point the measurement is made—essentially assuming a hydrostatic pressure effect (Hurd, 2007). This is reasonable because fresh concrete behaves like a fluid when the mixture is placed. However, in reality concrete is not a true fluid, and follows its own distribution of pressure. Figure 1 shows the distribution of concrete lateral pressures extensively used in Civil Engineering.

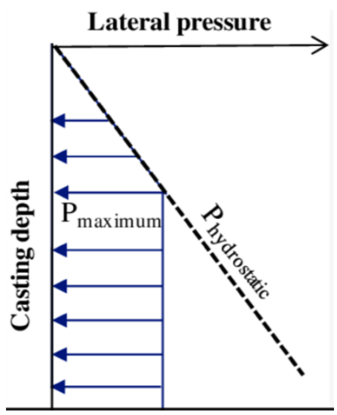

Figure 1. Lateral pressure diagram for fresh concrete. Source: (T. Proske, 2014)

Computing the maximum pressure, p_{max} is the first step in form design.

For the purpose of pressure determination, the ACI Committee 347 (American Concrete Institute, 2004) defines two equations for wall form pressure. The first, ***Eq. (1)***, applies to walls with a rate of placement less than 2.1 m/h and a placement height of 4.2 m or less.

The second equation, ***Eq. (2)***, applies to all walls with a placement 2.1 to 4.5 m/h, and to walls placed at less 2.2 m/h, but having a placement height greater than 4.2 m.

Equation 1.

$$p_{\max} = C_w C_c \left[7.2 + \frac{785R}{T+17.8} \right]$$

Equation 2.

$$p_{\max} = C_w C_c \left[7.2 + \frac{1156}{T+17.8} + \frac{244R}{T+17.8} \right]$$

- Where C_c and C_w are the chemistry and unit weight coefficients defined in Table2 and Table3 respectively
- R is the rate of placement [$^{m}/_{h}$]
- T is the temperature of the concrete during placement [°C]

Table 4. Chemistry coefficient C_c used in form pressure equations.
Source: (Hurd, 2007)

Cement type or blend	C_c
Types I, II, and III cements without retarders*	1.0
Types I, II, and III cements with a retarder	1.2
Other types or blends containing less than 70% slag or 40% fly ash without retarders*	1.2
Other types or blends containing less than 70% slag or 40% fly ash with a retarder*	1.4
Blends containing more than 70% slag or 40% fly ash	1.4

*Retarders include any admixture, such as a retarder, retarding water-reducer, retarding mid-range water-reducing admixture, or high-range water-reducing admixture, that delays setting of concrete

Table 5. Unit weight coefficient C_w used in form pressure equations.
Source: (Hurd, 2007)

Unit weight (density) of concrete	C_w (in.-lb version)	C_w (SI version)
Less than 140 lb/ft³ (2240 kg/m³)	$C_w = 0.5[1 + (w/145)]$ but not less than 0.80	$C_w = 0.5[1 + (w/2320)]$ but not less than 0.80
140 to 150 lb/ft³ (2240 to 2400 kg/m³)	1.0	1.0
More than 150 lb/ft³ (2400 kg/m³)	$C_w = w/145$	$C_w = w/2320$

Note: w = unit weight (density) of concrete, in lb/ft³ (kg/m³)

Vertical Loads
Design load for formwork are dead load plus live load per square metre of form contact area. The dead load is defined as the weight of the reinforced concrete plus the weight of the formwork.

The live load is defined as additional loads imposed during the process of construction such as material storage, personnel and equipment.

Formwork impact load is a resulting load from dumping of concrete or the starting and stopping of construction equipment on the formwork. An impact load may be several times a design load.

- Dead Load
  – Concrete and Rebar
  – Embedments
  – Formwork weigth

- Live Load
  – Personnel
  – Equipment
  – Mounting of Concrete
  – Impacts

This formwork will be subjected to High pressures. These pressures should be carefully determined, consulting engineers with specific knowledge of tunnel lining operations may be a good idea. Determining such a cross sectional pressure distribution will allow forms to be designed to withstand the working pressure and all the remaining dead loads and live loads.

FORM DESIGN

Determining the cross-sectional pressure distribution is the first step in panel form design. By computing the maximum pressure, the forms will be designed accordingly to withstand the working pressure. Maximum concrete pressure will depend on pour rate, concrete temperature, concrete slump, cement type, concrete density, method of vibration, and height of form. Maximum resistance to the pressure of fresh concrete for commercial products is around 60 kN/m^2

The formwork design aims at producing a form that is strong enough to handle the calculated loads safely and stiff enough to maintain its shape under full load. When designing concrete formwork, the following design simplifications and assumptions are made (Nemati, 2005):

1) All loads are assumed to be uniformly distributed.
2) Beams that are supported over three or more spans are considered to be continuous.
3) The design values for simple spans can safely be used for beams that are supported over two spans.
4) When determining size of main form members, the strength of nailed connections is neglected.

Typical Design Formulas include specifications for 3 checks for all the elements (Nemati, 2005).

- Bending check
- Deflection check
- Shear check

To design forms for Windcrete the previous checks will have to be realized to find the appropriate thickness and stiffness of the form panels to resist the acting pressure of fresh concrete. Unfortunately, these checks are beyond the scope of this work but will need to be done by future studies.

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