INITIAL COMPARISON OF CONCRETE AND STEEL HULLS IN THE CASE OF IDEOL'S SQUARE RING FLOATING SUBSTRUCTURE

Thomas Choisnet[1]; Bruno Geschier[1]; Geoffroy Vetrano[1]

[1]Ideol S.A.

Soon will start the construction of both versions of Ideol's square ring floater. Despite these hulls being constructed on different continents using different class rules, some key differences and comparisons are worth highlighting and reviewing. From initial conception through hull design, hull construction and launching, both concrete and steel hulls have their own specificities as well as their own areas where specific and particular attention need to paid. Ideol's square ring floater is currently the only solution that can be built using both materials, offering a unique flexibility in markets where either steel or concrete can be considered or where only steel of concrete are manageable given specificities of a local supply chain.

Keywords: Floating structure, offshore, wind energy, concrete, steel

INTRODUCTION

Originality of floating offshore wind turbine foundations

Floating offshore structures have been used mostly as storage facilities, breakwater of oil/gas production facilities. These structures either support heavy loads or need to meet stringent motion criteria to enable equipment to operate in reasonably broad weather conditions.

When it comes to supporting a wind turbine, the motion performance and payload constraints are not so stringent as other applications: a typical 6MW wind turbine rotor-nacelle assembly will weigh around 400tons and will be able to sustain tilting in operation around 10degrees. Wind loads are however much larger for wind turbines than on drilling facilities. In operating conditions, the ratio of the wind heeling moment to the displacement of the structure is typically 50 times larger for a floating wind turbine than the biggest drilling vessels.

Floater design drivers, the damping pool® case

The floaters featuring the damping pool ® are essentially ring-shaped flat hulls.

Figure 1. View of 6MW damping pool

They provide a stable and economic platform to support wind turbines by featuring a large water plane area and a combination of passive hydrodynamic motion damping features. More details can be found in [1]. Concrete as a material for floating structures has the disadvantage that its self-weight for a given volume is larger than for steel structures. The limited payload required to support a wind turbine makes it possible to design concrete structures that would have the same dimensions as a steel structure.

For a damping pool floater, the ratio between the moonpool size and the breadth of the floater is fixed by the performance of the moonpool damping characteristics. Hence once the breadth of the hull is fixed, the size of the moonpool can be defined. The breadth is actually driven by the required hydrostatic stability of the floater. This stability performance is actually independent of the draught of the floater. The heel hydrostatic stability modulus is given by:

$$K_\theta = GM.\Delta = (KB - BM).\Delta \qquad (1)$$

$$BM.\Delta = (I_0/V).(\rho.V) = \rho.I_0 \qquad (2)$$

As most of the mass of the floating wind turbine is concentrated in the hull, the distance between the centre of gravity and centre of buoyancy will only change by a proportion of the depth of the hull, when the metacentric radius *BM* is constant and much larger. Hence the stability is only dependent on the waterplane inertia at first order.

In summary the selection of the dimensions of the floater can be summarized as follows:

1- Select the wind turbine and define wind loads,
2- Define the horizontal dimensions of the floater based on wind loads and moonpool sizing rules,
3- Adjust draught to meet sea-keeping performance.

Dimensions for a 6MW turbine are provided in table 1 below. Both hulls have the same displacement and waterplane area which makes their stability performance equivalent. Their dimensions are slightly different for structural arrangement reasons.

	Concrete	**Steel**
Breadth	47m	45m
Moonpool width	27m	27m
Depth	10.5m	11m
Displacement	10'900t	10'000t
Waterplane area	1'380m²	1'300m²

Table 1. Dimensions of 6MW floaters.

DESIGN FEATURES

Structural arrangement and ballasting

Both hulls are made of float panels in order to ease their construction. The hulls are split into several compartments so that they can sustain a breech in any of the compartments. The structural arrangement is actually similar for both hulls: flat panels reinforced by transverse web frame. The size of the compartments is driven by the damaged stability verification. In practice all compartments have a nearly equal volume.

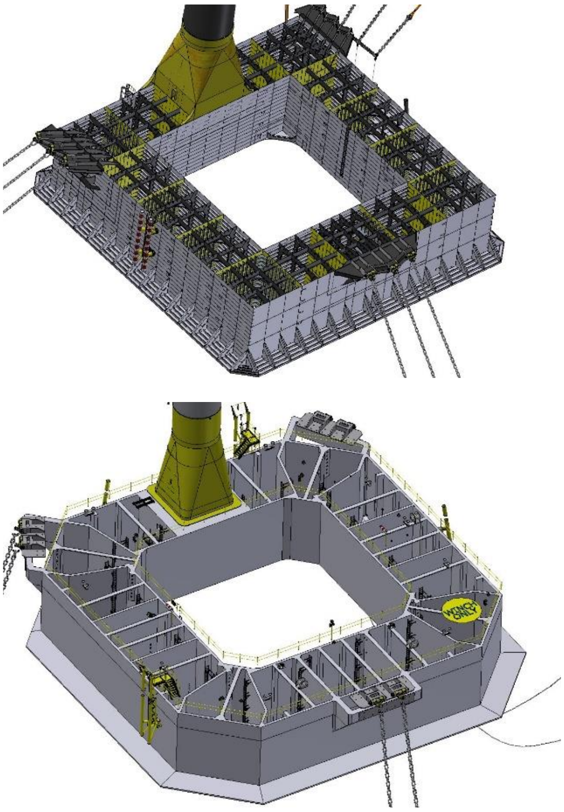

Figure 2. View of structure for 6MW floaters: steel (top) and concrete (bottom)

One can see on the pictures above that the outside shell of the steel hull forms a square, whereas that of the concrete hull forms an irregular octagon. The more complex outside shape of the concrete hull is actually meant to ease the connection of the mooring foundations to the hull. This will be discussed below.

The quantity of ballast that the steel hull needs to contain is large: as the hull is light and carries equipment (the turbine, tower and transition piece) worth only around 10% its displacement, it needs to be ballasted to meet its operational draught. Given the large amount of ballast, it is preferable to fill them with seawater which will be free. Hence in operation, half of the compartments will be full of water. In the case of the concrete floater, there will be water in a limited number of compartments only. Details of the weights are provided in table 2 below.

	Steel	**Concrete**
Displacement	10'000t	10'900t
Hull weight	2'200t	8'250t
Ballast weight	6'400t	1'600
Ballast (% of displacement)	64%	15%

Table 2. Structure and ballast weight for 6MW floating wind turbine

Watertightness, durability

Steel plating is fully watertight. Concrete, however will crack in the most stressed areas. It is consequently necessary to control that these cracks will not cause water leakage into the hull. This is done by maintaining under compression a portion of the thickness of the concrete walls. Under these conditions, it is ensured that no through-thickness cracks will occur.

As the hulls are subject to global bending loads, the walls could well be in tension across their thickness. This is prevented by applying pre-stressing loads to the structure, which guarantees the water-tightness of the hull, as may pre-stressed concrete tanks or offshore structures. Hence the concrete hull needs to be pre-stressed. An example

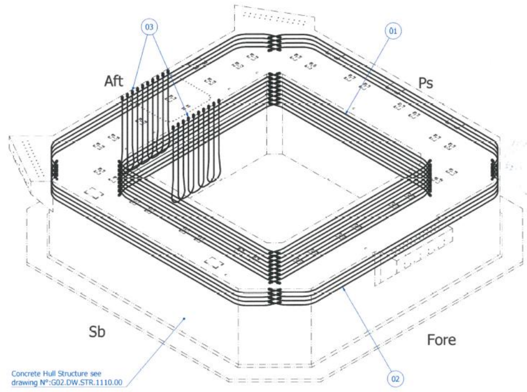

Figure 3. View of pre-stressing cables in a typical floating wind turbine

Pre-stressing is necessary in way of the tower to counter the tower bending moment, and in the sides to counter global hull bending loads.

Corrosion protection is due to last 20years as the structures will be unmanned and far from the shore. The steel hull is simply protected by epoxy-based coatings and sacrificial anodes. The steel reinforcements of the concrete hull are protected by ensuring that the cracks that may appear on the concrete hull will not open more than pre-set criteria (0.2mm to 0.4mm depending on the area and rules), by adequate concrete cover of the rebars, and eventually by using cathodic protection for those areas which are exposed to sea-water.

The operation and maintenance of both units will be similar provided the design life remains within 20years. For larger lifetimes, the concrete hull will have superior qualities.

Details of connections

The floating foundation is designed to remain onsite during storms. This causes the mooring system and hull loads to be rather large. Typical orders of magnitudes for a 6MW units are between 1'600t and 4'000t combined breaking load of the mooring chains of a cluster.

These loads are concentrated and need to be spread to the hull. The principles of the connection of mooring lines to the hull are to spread loads from the mooring line to hull by using a series of materials with decreasing strength as the load is spread. Hence, the chain and connectors have a yield stress around 540MPA, the next connection is high strength steel around 420MPa in way of the padeyes directly in contact with the mooring line, then a steel structure with yield stress of 355MPa and eventually bolts enable to connect this steel hull to concrete. For the steel hull, we simply weld to the hull the 355MPa steel structure. Pictures of the mooring foundations are shown below.

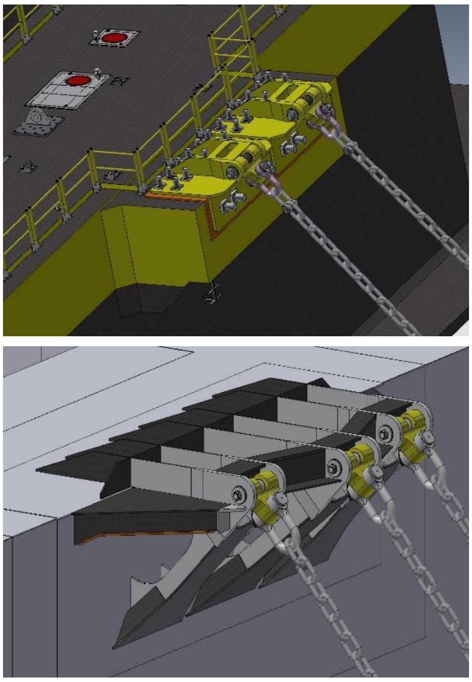

Figure 3. Views of mooring foundations for a concrete hull (top) and a steel hull (bottom)

The same principles apply for the tower transition piece: it is welded to the steel hull and bolted to the concrete one (see figure 2 for an overview of the assembly)

The mooring foundations are driven by ultimate loads whereas fatigue loads define the scantling of the tower transition piece.

OPERATIONAL CONSIDERATIONS

Carbon content

One of the main objectives of wind turbines being to reduce CO_2 emissions in energy production, it is worth comparing the CO2 emissions related to the fabrication of the base materials for both options.

The calculation is performed for the concrete and steel hull according to the guidance of the ADEME's (the French Agency on energy and the environment) Base Carbone ® [2]. Two scenarios are proposed for these calculations: one case where only new material is used and a more optimistic one where recycled steel and blast furnace cement is used. The carbon content is nearly twice better for a concrete hull, whatever the case. Calculations are detailed in table 3 below.

	CO2 emissions per tonne purchased	**Quantities - concrete hull**			
		New materials		Recycled	
		t	tCO2	t	tCO2
Portland cement	866 $kgCO_2/t$	1000	866	700	606
Blast furnace cement	0 $kgCO_2/t$	0	0	300	0
Fresh water	4 $kgCO_2/t$	400	2	400	2
Aggregates	3 $kgCO_2/t$	5563	17	280	1
Recycled steel	1100 $kgCO_2/t$	0	0	781	859
New steel	3190 $kgCO_2/t$	781	2492	0	0
Total emissions - concrete hull			3376		1468

	CO2 emissions per tonne purchased	**Quantities - steel hull**			
		Worst case		Best case	
		t	tCO2	Best case	tCO2
Recycled steel	1100 $kgCO_2/t$	0	0	2200	2420
New steel	3190 $kgCO_2/t$	2200	7018	0	0
Total emissions - steel hull			7018		2420

Table 3. CO_2 emissions for a 6MW hull in concrete (top) and in steel (bottom)

Construction

The construction methods of the steel hull will be very similar to those of a ship structure. As the hull is made of plated structures fitted with stiffeners, it will be adequately built using shipyard techniques. The productivity of these techniques relies on the automation and optimisation of individual operations: steel cutting, bevelling, welding, etc. These operations necessitate specialised equipment which cannot be moved from site to site. When local construction is required, it will consequently be necessary that a shipyard or steel construction shop is located in the vicinity of the project. There will be little gain in productivity when building a single hull or 50 hulls: the operations in steel construction are optimised at the most individual elementary level: cutting and welding. These hulls are typically built by assembling panels, making up blocks and welding these blocks together.

The main challenge in building concrete hulls is to be able to assemble and launch them. As these hulls are heavy, they cannot easily be handled.

The main options offered to build a concrete hull are:

1- Build the complete hull on a quay / barge and float it off ;
2- Build the bottom and part of the walls, launch, then complete erection of the walls afloat ;
3- Build the hull up to the top of the walls on a floating dock, then complete deck afloat ;
4- Build the hull in modules that can be more easily transported assemble them on either a barge or in a drydock and float them off.

For series production, option 1 is not efficient enough. Completing afloat or building in module are consequently the most likely options to be used on a given project. Option 2 can be interesting when access to sheltered waters for launching or a drydock are not easily available. Option 4 will be the preferred option in deepwater ports with a large number of units being produced. The construction methods can consequently be adapted to the site under consideration.

Cost and volatility

The volatility of steel is well known as the steel mills are slow to start or stop. On the period ranging between 2008 and 2012, steel billet purchase price has ranged between 250$ and 1250$ [3] while the cost of cement in France [4] has been stable, that is within +/-3%.

Even though the supply of the base steel is not the only factor affecting the cost of steel construction, its volatility makes steel structures construction within +/-25% variations possible in a matter of a few months.

On the contrary, concrete structures are less affected by supply volatility as reinforced concrete structures feature approximately three times less steel, and other constituent are stable in price.

Based on the figures above, one can provide a cost of 1300€/m3 of concrete and 4000€/ton of steel. This yields, for hulls built in Europe to a concrete hull approximately twice cheaper than for a steel hull. The equation can however be different when steel construction is more productive than in Europe, and when aggregates are not readily available (which happens in some places, in particular Island states).

CONCLUSION

In general steel or concrete prove to be equivalent in terms of performance of a floater. The dimensions are adjusted on the basis of the wind loads that the wind turbine will apply to the foundation, and the target seakeeping performance of the floating wind turbine.

Once the dimensions are fixed, the main criteria that will lead to select one material versus the other are the availability of facilities adapted to the construction of steel structure, the necessity to build the hull locally and the carbon content target.

The carbon content of a steel hull is twice as large as that of a concrete hull of the same dimensions. This can make in itself an argument of choice to select concrete. The construction method will in addition be dependent of the site for a concrete hull.

However, depending on the area of deployment of the hull, it may be preferable to build the hull in steel. It is also important to offer the possibility to build both in case the market trends change and either reduces or increases the cost of steel structures.

REFERENCES

[1] T. Choisnet et al., “A robust concrete floating wind turbine foundation for worldwide applications”, *Proceedings of grand renewable energy, Tokyo, 201*.

[2] ADEME “Documentation des facteurs d'émissions de la Base Carbone ®” 2016

[3] London metal Exchange database, Steel billet

[4] INSEE “Indice de prix de production de l'industrie française pour le marché français - Prix de base - CPF 23.51 - Ciment - Base 2010 ”