FIP Symposium '93
Kyoto, Japan
Oct. 17-20, 1993

Prestressed Concrete
Engineering Association
Tokyo, Japan

The Salhus Floating Bridge

Per Meaas and Elljarn Jordet,
Dr.Ing. A.Aas-Jakobsen A/S, Norway

John H. Gustavsen,
Norwegian State Highway Dept.Norway

Einar Landet,
DNV Industry Group, Norway

SUMMARY

The Salhus Bridge across the Salhus fjord in Western Norway will replace the car ferry service having the heaviest traffic in Norway. The bridge will be opened for traffic in December 1993. The total bridge length is 1615 m and consist of a high level cablestayed bridge 369 m long and a floating bridge 1246 m long. The beam in the cable stayed bridge and the pontoons for the floating bridge are designed in light weight aggregate (LWA) concrete with density 1900 kg/m^3 and compression cube strength 55 MPa (quality LC 55). The bridge and some of the prestressing arrangements are described.

1. GENERAL

The project involves access roads a high level cable stayed bridge providing a ship channel and a floating bridge between the underwater rock Klauvaskallen and Flatøy, see Figure 1 and 2.

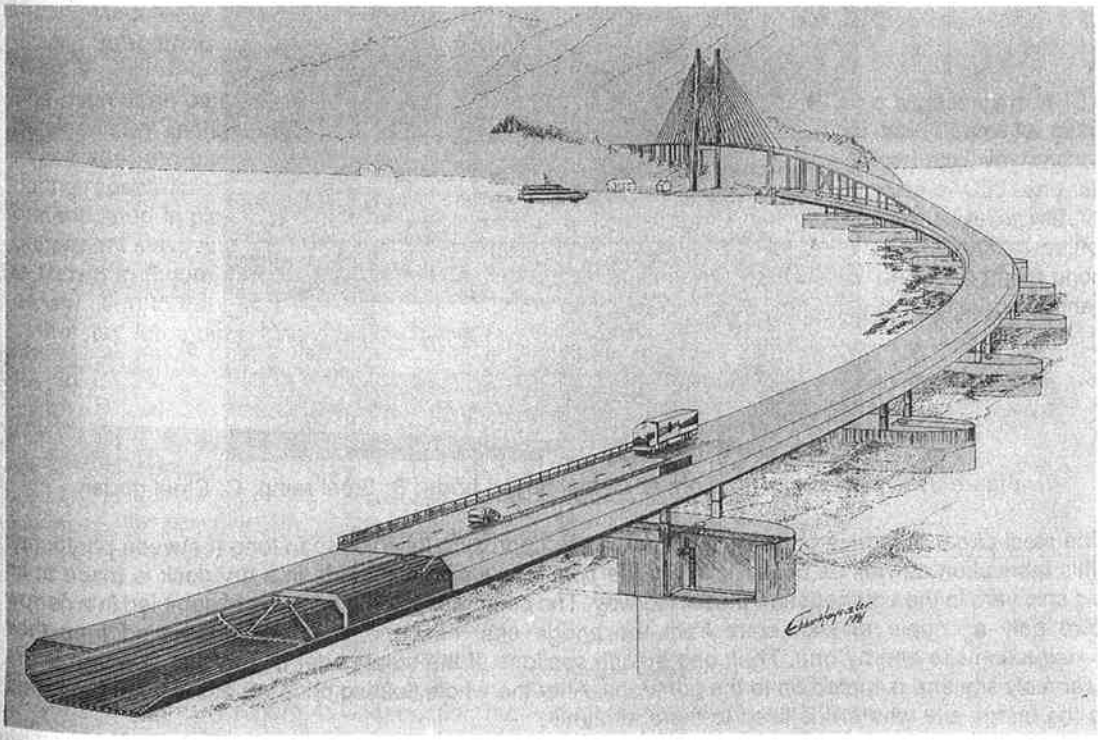

Figure 1: Artists impression

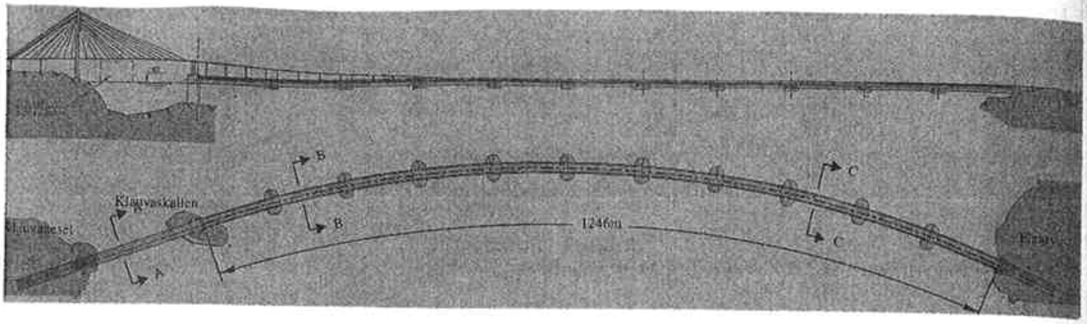

Figure 2: Section and plan view

The steel box girder of the floating bridge forms a circular arch with a radius of 1700 meters in the horizontal plane. The girder rests on 10 pontoons. The pontoons are positioned with a center distance of 113.25 m and acts as elastic supports for the girder. The girder is designed without internal hinges. The bridge follows the tidal variations by elastic deformations of the girder.

There are two traffic lanes and a pedestrian sidewalk. Further, the bridge is designed for a future widening to three traffic lanes and the addition of a new cantilevered sidewalk. The typical cross-sections of the bridge are shown in Figure 3.

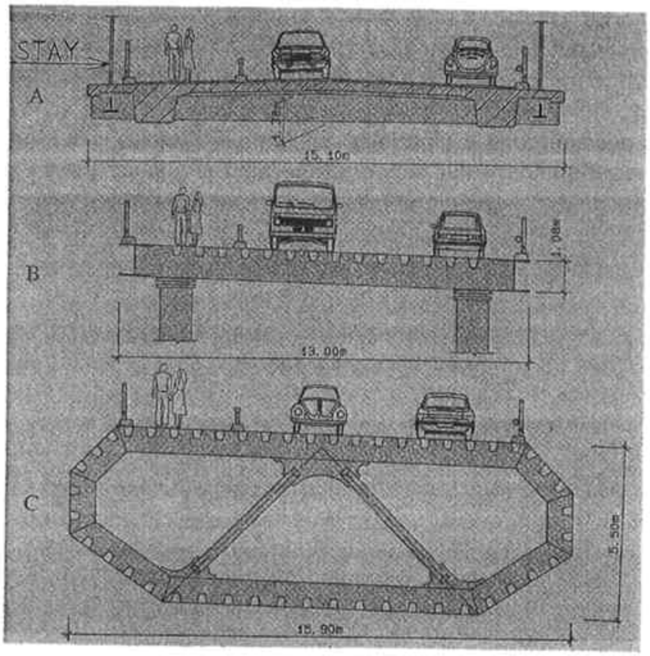

Figure 3: Typical cross-section; A: Cable stayed bride; B: Steel ramp; C: Steel girder

The steel girder is fabricated in sections which are approximately one span long (between pontoons). This fabrication as well as construction of the pontoons which are made in a dry dock is made at an old ship yard in the southeastern part of Norway. The complete floating bridge is assembled in a narrow fiord only a couple of kilometers from the bridge site. First the pontoons are towed from their construction site one by one. Then one by one sections of the steel girder is towed on a barge to the assembly site and is mated on to the pontoons. After the whole floating bridge is assembled it is towed to the bridge site where it is fixed to the abutments.

2. DESIGN OF THE HIGH LEVEL CABLE STAYED BRIDGE

The high level bridge shall provide a clear ship channel of 32 m x 50 m, see Figure 1 and 2. A cable stayed bridge design was selected from several other alternatives. This bridge combine high aesthetical qualities with an economical and functional design. The main span is cantilevering 163 m from the tower on the existing rock Klauvaneset. The free end is supported by a monolithic T-structure on the floating bridge abutment, which also supports the transition ramp from the floating bridge. This geometry is determined from the requirement that the joint in the floating bridge and the transition ramp must be located in the some vertical plane. The joint to the high level bridge cantilever is then located to obtain the best balance of forces in the T-structure.

The main span cantilever is stabilized by the approach bridge. The structure is designed for the wind speed of 26.9 m/s (10 min. mean at elevation 10 m above sea level) with turbulence intensities (ratio to V_{10}) I_H = 0.20 horizontal and I_v = 0.10 vertical.

The main span bridge beam shown in Figure 3 is designed in LWA concrete LC55. This design was found to be economical due to savings in stay cable quantity, even if the beam itself is a little more expensive due to a higher cost of the concrete material. The total cost savings was found to be in the order 5%. The LWA concrete has the following mix design and properties:

430 kg Portland cement
35 kg Silica
630 kg sand 0-5 mm
295 kg Leca 4 -8 mm
275 kg Leca 8-12 mm
195 l water total
7 l Plasticizers and superplasticizers

- Theoretical density is 1893 kg/m^3 assuming 7.5% water absorption in the clay aggregate.
- Modules of elasticity E_c = 21000 MPa
- Strength fck = 62 MPa (mean, on 100 x 100 cubes)

The main span beam is monolithic with the cross beam in the tower, and has a typical span of 12 m between stay anchors. Posttensioning tendons are provided in the longitudinal main beams for global forces after the bridge is completed, and in the transverse beams for local forces and stay anchors during construction. The stay anchors are designed in normal weight concrete C55 and are prefabricated in place. This design makes it possible to support the form and form traveller with the permanent stays and anchors during concreting of each new bridge segment. The construction method is shown in Figure 4. One external steel strut from each prefabricated anchor of the segment under construction to the previous already completed anchor is provided to carry the horizontal component of the stay force during the concreting.

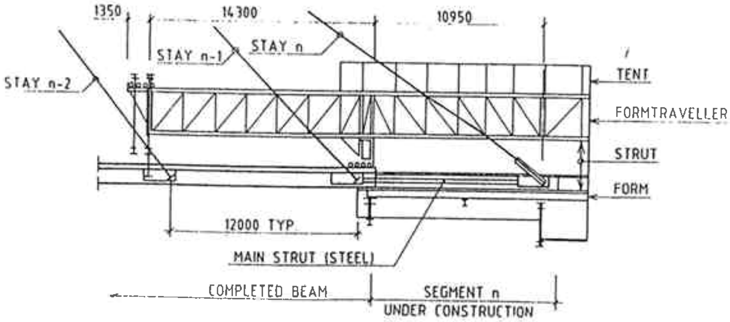

Figure 4: Construction method for cable stayed main beam.

The formwork is bolted to the completed cantilever and prestressed to the prefabricated stay anchors with rods Ø 36 mm. When moving forward the form is supported by the traveller at the free end, and rolls on the edge beam of the bridge slab at the back. The actual form traveller is placed above the bridge deck and is supported on the main longitudinal beams. This form traveller is designed with a bending stiffness of min. 80% of the bridge beam stiffness to provide a stiff support structure during concreting and hardening of a new segment. Also the form traveller supports a "tent" which gives full cover for all works done when building a new segment. These design requirements are very important in the windy and rainy area of western Norway.

The main beam segments were built with a working cycle of two weeks for the first 5 segments, reduced to one week for the last segments. The progress has been somewhat delayed due to high winds and restrictions in operation on the tower crane. The form traveller, however, has functioned very well.

The tower is designed in normal weight concrete C45. An H-shape design was considered to be more suitable than an A-shape as it is easy to construct and render itself to simplicity in all stay anchor details. Also the foundation topography as well as aesthetic considerations favored the H-shape.

Each leg has a box section with dimentions B/L/T, where B is 2400 mm, L varies from 4000 to 4983 mm and T is 400 mm typical and 1000 mm where the stay anchors are located. Posttensioning is provided in each cross-beam and as hoop tendons in the stay anchorage zone. The tower was constructed by slipforming.

The approach bridge is designed in normal weight concrete C45 and has a similar cross section as shown in Figure 3. In the area of back stay anchors the main beams are widened to provide stabilizing selfweight for the main span cantilever. Also rock anchors are provided in the columns in this area for the same reason.

Fully prefabricated stays were considered necessary for this bridge which is constructed during severe weather in the winter in Western Norway. The Stahlton stay with galvanized 7 mm wires, HiAm anchors and high density polyethylene (PE) tubes filled with special grease were finally chosen. The PE-tubes are strengthened in the area of the neoprene washers (dampers) near the anchors. Here an extra PE protection tube was provided together with a stainless steel plate protection bearing against the washer which have a PTFE wearing surface vulcanized on the inner circumference. Also secondary stiffening wires in stainless steel will be provided, interconnecting the stays to prevent stay vibration.

3. DESIGN OF THE FLOATING BRIDGE

In the steel girder steel qualities are used which are usually used in the offshore industry with yield strength varying from 355 MPa to 540 MPa. The highest steel quality is used in the area from the abutments and past the first pontoons.

The steel box girder is fixed to the abutments by means of special purpose made "flexible" plate connections made in high strength forged steel. (yield strength f_y = 500 MPa). The plate connections transfer bending moments about a vertical axis, axial forces and horizontal shear in the girder to the abutments. The plate connections however, are flexible about a horizontal axis perpendicular to the bridge in order to allow deformations due to tidal variations. Vertical shear and torsion is taken by separate bearings.

In addition to the "normal" bridge loads such as dead load, traffic load and static wind load, the bridge is designed for dynamic effects of wind and waves, tidal effects and current. The environmental loads resulting in the most severe load actions are dynamic waves, dynamic wind and tide. The design is based on a return period of 100 years for the environmental loads. The significant wave height is H_s = 1.69 m with a peak period varying from T_p = 3.6 - 5. 1 seconds. The 10 min. mean wind speed applied is v = 27.1 m/s. The tidal variation is ± 1.5 m. The resulting load effects for the girder in a section under the viaduct above the pontoon nearest to the abutment is given in table 1.

Load	Px (MN)	Mx (MNm)	My (MNm)	Mz (MNm)
Dead load	0	0	105	0
Traffic	0	0	67	0
Dynamic wind	6	14	27	43
Dynamic wave	20	52	142	115
Tide	0	0	108	0

Table 1: Typical global forces in the steel girder

The girder is checked in the fatigue limit state considering the effects of waves, wind, traffic and tide. For the wave effects a stochastic fatigue analysis is performed. The design life is 100 years.

The accelerations due to wave and wind loads are also checked. The maximum horizontal acceleration at bridge deck level is 0.6 m/s^2 considering loads with a return period of one year.

4. CONCRETE PONTOONS

All of the 10 pontoons are 42.0 m long and 20.5 m wide and with a half circle of diameter 20.5 m at each end. The draft varies from 4.3 m to 5.6 m while the freeboard is 3.0 m for the pontoons next to the abutments while the other pontoons have a freeboard of 2.6 m.

Each pontoon is divided into 9 compartments which are separated by watertight bulkheads. Each compartment has access through a watertight hatch from the top deck. The size of the compartments are determined such that the floating bridge is still intact if two adjacent compartments are flooded due to some accident.

The thickness of the base slab is 300 mm, the outer walls are 310 mm thick while the top slab and the internal bulkheads are 200 mm thick.

LWA concrete, LC55, has been used in the entire pontoons in order to reduce weight as much as possible. A reduction of weight is favorable because the draft is reduced which again reduces wave and current loading on the entire structure.

The main properties of the LC55 concrete are similar to those of the LWA concrete in the main span of the cable stayed bridge.

- E–modules: 20.000 – 23.000 MPa
- Density (saturated) is maximum: 1950 kg/m^3
- Type of aggregate: Liapor 8

The most critical design criteria are those for the Serviceability Limit State:

- the minimum height of the compression zone in any cross section shall be at least 100 mm in order to ensure watertightness
- the crack width shall be less than 0.2 mm in the splash zone and less than 0.5 mm otherwise.

Although the floating bridge is a dynamically sensitive structure the governing loads on the pontoons are mainly the effects of hydrostatic water pressure.

As result of the above mentioned design criteria an ortogonal net of prestressing tendons are placed in the bottom slab. These are tendons mainly with 1 or 2 strands in each duct. All tendons are stressed from the inside of the pontoon. In the walls only vertical tendons are used. These are formed as U-cables which are all stressed from the top of the walls, see Figure 5.

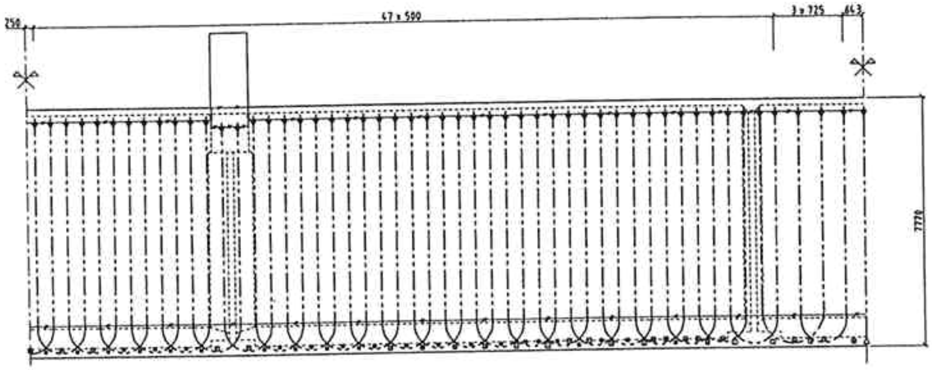

Figure 5: Typical prestressing arrangement in the external walls.

In the top slab no prestressing is required except 2 transverse tendons between the pedestals for the steel box girder.

The ordinary reinforcement is generally Ø16@150 mm allover. Only in some local areas additional reinforcement is required. Maximum twice of the minimum reinforcement is used.

The free height between the waterline and the underside of the steel box girder is 5.5 m which is to allow passage of small boats. Due to this the steel box girder has to be supported on pedestals on the pontoons. These supports are provided by means of modified normal bridge bearings. In order to minimize the loading due to horizontal deformations at the supports two bearings are free to move horizontally while two are fixed. The two fixed bearings are placed diagonally opposite of each other. In an accidental situation there will be tension forces in the bearings. These forces are carried by 8 prestressing bars at each of the fixed bearings.

5. FLOATING BRIDGE ABUTMENTS

One abutment form the transition between the high level bridge and the floating bridge. This abutment is founded on bedrock at a waterdepth of 30 m. It consist of a caisson with a cross section of 20 m x 21 m with 16 internal cells. The caisson is filled with gravel and it is closed with a slab 5 m above the waterline. On top of this slab massive anchor blocks are arranged to provide fixation of the floating bridge and to provide foundations for the columns of the T-structure that supports the high level bridge.

The other abutment is placed on land. This consists basically of a massive concrete block which is 22 m long, 20 m wide and 14.5 m high. This block is cast in place directly against blasted rock surfaces.

The largest loads to be carried by the abutments are axial forces in the floating bridge in combination with a moment about the vertical axis of the abutment. Vertical prestressed rock anchors are required to provide sufficient stability. In one abutment 12 tendons are used, and in the other 14 tendons. The total tension force is approximately the same; 42 -44 MN. The size of the abutments are designed such that they are stable also without rock anchors, but then reduced load factors are applied.

The bearing system for the floating bridge is briefly mentioned in section 3. Neoprene bearings are used to support vertical forces. On each side of the steel girder it is one set of neoprene bearings supporting downward vertical forces and another set supporting upward vertical forces. At each abutment 4 "flexible" steel plate connection elements are used. This arrangement is shown in Figure 6.

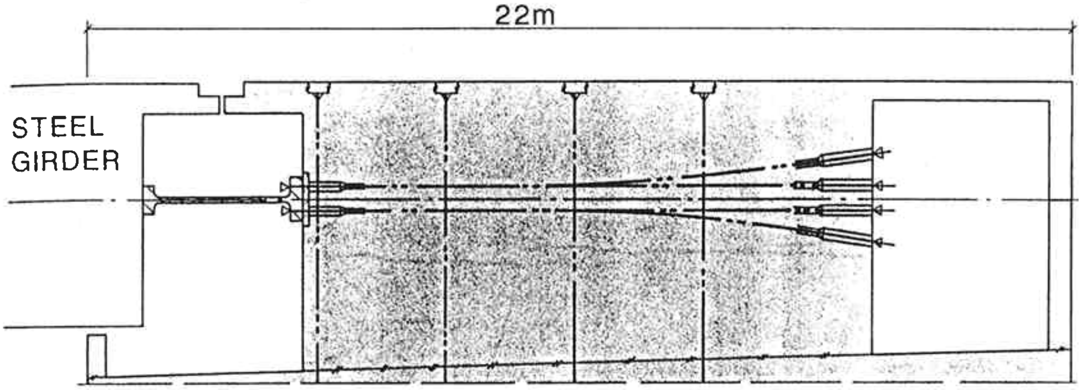

Figure 6: Arrangement for fixing of the floating bridge to the abutment

The steel plate connection elements are fixed to the steel girder by means of bolts. The fixation to the abutment is provided with 32 tendons in each abutment. Each tendon has 37 No. 15 mm strands and is tensioned to 7.35 MN. The tendons are short; 10.3 m and 12.8 m respectively. Tension losses are therefore carefully calculated. In order to provide sufficient compression stress capacity behind the steel connection elements, thick steel foundation plates are used to distribute stresses, and concrete quality C75 combined with a dense reinforcement is used at least 2.5 m behind the foundation plates.

6. CONCLUSIONS

This project shows successful use of prestressed high strength LWA concrete in two situations where weight savings provide significant savings in the costs of other elements. For the cable stayed bridge costs of stay cables are reduced and for the floating bridge weight and costs for structural steel in the main girder is significantly reduced.