Ferry free E39 –Fjord crossings Bjørnafjorden | 304624

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FJORDCROSSING PROJECT E39

Verification Summary Report E39 Bjørnafjorden

SVV

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Objective: Verification summary report showing the four-year work executed by DNV GL related to advisory, control and quality checking of documentation produced by designers for the E39 fjord-crossing project.

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Keywords:
Floating bridges, verification, advisory, Bjørnafjorden, suspension bridges, safety levels, independent analyses, reviews, control, aluminum

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1 EXECUTIVE SUMMARY

With basis in a 4-year (2016 – 2020) Frame Agreement (FA) with Statens vegvesen, Region vest (SVV) DNV GL has performed a high number of verifications, control and advisory activities related to the E39 fjord-crossing project between Trondheim and Kristiansand. This has been an evolution with evaluations and analyses of many floating bridge alternatives. Main focus has been on the 5 km record long Bjørnafjorden (BJF) crossing, hence BJF is the focus in this report per advice from SVV.

In the last phase (5) which ended in the summer of 2019, two design groups (AMC & OON) evaluated, analyzed and ranked 4 different (K11, K12, K13, K14) floating bridge alternatives for the BJF crossing. Both groups recommended the same alternative, K12 and DNV GL agreed to the selections made. These two K12 concepts were also subject to comprehensive review and analyses by DNV GL. **The main conclusions made by DNV GL from these independent verifications were that we find the concepts feasible and do not see any showstoppers, but that there are some improvement areas that should be looked further into for the next design stages.**

Floating bridge concepts that were ruled out early for BJF were the submerged floating tube concept (pontoon & tether supported) and the TLP foundations (two) suspension bridge concept. DNV GL agreed to this.

Several alternative solutions have been evaluated during the period for the selected BJF pontoon bridge concept. At some point the bridge curvature was also changed from south/west to east and with ship channel in south end. The four final alternatives that were considered in phase 5 were:

K11 – Curved, end-anchored floating bridge in accordance with phase 4 (internal SVV phase) of the project

K12 – Curved, end-anchored floating bridge with supplementary side moorings

K13 – Straight, side anchored floating bridge

K14 – 'Straight' S-shaped, side anchored bridge

Typical further focus areas (further details given in the back of this report) pointed out by DNV GL related to the two selected K12 alternatives are:

- ULS strength in some parts of the bridge system, e.g. tower and North end and possibly consider higher strength steel
- Possibly allow for an ALARP philosophy in regard ship collision/impact
- Fatigue in general and fatigue due to local traffic loads and further look into the influence of the asphalt layer
- Installation aspects with complex marine operations

- Further develop/refine metocean design basis
- Revisit parts of the mooring system/design, e.g. bottom chain

Figure 1-1 AMC K12 concept, seen from the south end

Figure 1-2 OON K12 concept, seen from east

During the last half year of this contract a lot of focus has been on the possible use of aluminum in a 1200 m long suspension bridge across Langenuen. This is also an important crossing along E39 between Stavanger/Haugesund and Bergen and steel alternatives are already considered suitable. Activities included document review of the design documents and independent local and global analyses. A separate review was also made related to the possible installation of a one-piece steel pylon from the seaside. This review focused mainly on marine operations.

Two different (panel & plate) cross-sections were analyzed by DNV GL and the global dynamic wind analyses revealed responses comparable to those documented by the designer. The local FE analyses did however reveal challenges in regard fatigue due to traffic loading. Subsequent to these analyses there has been made changes to the bridge girders to improve the fatigue lives and further work is ongoing.

2 INTRODUCTION

On behalf of SVV, DNV GL has been involved in a very interesting journey the last 4 years related to the so-called ferry-free project (E39) between Trondheim and Kristiansand (see Fig. 2-1). The term ferry-free has been somewhat abandoned the last year, but the project objective still applies. The main objective with this E39 project (Trondheim – Kristiansand) has been to reduce the travel time by car from 21 to 11 hours by installing new fjord crossings along E39.

In this 4-year (2016 – 2020) frame agreement (ref. /1/) with SVV the main focus for DNV GL has been for the record setting Bjørnafjorden (5 km crossing) and some minor efforts towards Halsafjorden and Julsundet. The last year also contained some comprehensive efforts (reviews and local/global analyses) of a possible 1200 m long aluminum suspension bridge across Langenuen between Stord and Tysnes.

DNV GL has made use of in-house specialists within many disciplines and about 90 persons have been involved over these 4 years. Main efforts from DNV GL have been within the structural, hydrodynamic and advanced time domain simulations. The structural focus has been on steel (fatigue & ultimate) and the last year aluminum for the Langenuen suspension bridge. Simulation of hydrodynamics, static and dynamic wind loading, and relevant damping effects have been central for the analysis work performed by DNV GL. Use of and experience with state of the art software have been crucial and DNV GL has used the SIMO/RIFLEX software for the time domain simulations with hydrodynamic input from WADAM and the wind gust program TURBSIM.

Other areas that should be mentioned are review of design basis documents within metocean, geotechnical, structural and mooring. Some activities within technology qualification (TQ) and the last year with focus on material aspects (steel, aluminum and laser-/hybrid welding).

Subsequent to the BJF phase 5 verification effort in the fall of 2019 DNV GL performed an interesting and challenging study for SVV to assess the inherent ULS safety level in the design basis for the BJF floating bridge. How the results from this study/work will be used is up to SVV.

Figure 2-1 E39 project fjord crossings between Trondheim and Kristiansand

3 ABBREVIATIONS

Table 3-1 Abbreviations

Abbreviation	Explanation
AL	Aluminum
ALARP	As Low As Resonably Possible
AMC	Aas Jacobsen Multiconsult Cowiconsult
AR	Action Required (NPS)
BJF	Bjørnafjorden
DFF	Design Fatigue Factor
FA	Frame Agreement
FE	Finite Element
FDV	Forvaltning Drift Vedlikehold
FLS	Fatigue Limit State
HA	Halsafjorden
IN	Important Note (NPS)
JU	Julsundet
LA	Langenuen
MHW	Mean High Water
MHWS	Mean High Water Spring
MLWN	Mean Low Water Neap
NPS	Nauticus Production System
NS	Norsk Standard
OON	Olav Olsen Norconsult
RFC	Rain-Flow Counting
SAFB	Submerged Arched Floating Bridge
SCF	Stress Concentration Factor
SIMO/RIFLEX	SINTEF TD simulation software
SVV	Statens Vegvesen Region Vest
STF	Stress Transfer Function
STFB	Submerged Tube Floating Bridge
SRA	Structural Reliability Analysis
TD	Time-domain
TechDoc	Technical Document (NPS)
TLP	Tension Leg Platform
TQ	Technology Qualification
TURBSIM	Turbulent wind simulation software
ULS	Ultimate Limit State
WADAM	DNV GL hydrodynamics software

4 FRAMEAGREEMENT - BASIS FOR WORK

Frameagreement 15/255967 between SVV and DNV GL was established in May 2016 and valid from 02.05.2016 to 01.05.0218. The contract had options with a maximal duration of 4 years (2+1+1) and was later extended to 01.05.2020.

Per agreement with SVV, activities approved prior to the end date could continue after 01.05.2020. As of June 2020, this applies to two activities 415 & 710 that have end dates in 2021. Both these activities are related to laser/-hybrid welding; 415 related to the qualification process and 710 related to actual application on a walking bridge in Vanylven/Åfjorden.

The focus of the frame agreement has been advisory, control and quality assurance for the fjord-crossing project E39 between Trondheim and Kristiansand.

Main focus during these 4 years has been on Bjørnafjorden, but also some minor activities related to Halsafjorden and Julsundet. The last year also high focus has been placed on Langenuen with the possible use of a 1200 m long suspension bridge built in aluminum across the narrow in Hordaland/Vestland.

5 ACTIVITIES PERFORMED BY DNV GL

A total of 63 activities have been approved and executed as shown in Table 5-1. In general, the activity numbers given reflect the timeline. Note that the two activities 415 & 710 have an end date in 2021 and how to follow up these will be decided after the summer of 2020.

About 90% of the activities performed are related to Bjørnafjorden and floating bridge concepts considered for this record setting 5 km crossing. The last year of the contract focused a lot on Langenuen and the possibility of using an aluminum suspension bridge. Two cross-sections (plate & panel) were looked into and analyzed (local and global analyses) by DNV GL.

Table 5-1 List of activities

Activity	Title
100	Prosjektledelse, administrasjon og QA/QC
100.1	Prosjektledelse, administrasjon og QA/QC
110	Prosjektoppstart
111	Etablere arbeidsordre
120	Sluttrapportering
200	Etablere basis for verifikasjonsprosjektet
201	Presentasjon av forankringssystemer
210	2.1 Design basis - Gjennomgang av dokumentasjon

Activity	Title
220	2.2 Miljødata - Gjennomgang av dokumentasjon
230	2.3 Grunnundersøkelser - Gjennomgang av dokumentasjon
240	2.4 Skipsstøt - Gjennomgang av dokumentasjon
250	2.5 Rørbru - Etablere risikobasert verifikasjonsplan
251	Uavhengig analyse av rørbrukonsepter
254	Konseptverifikasjon av rørbru – fase 2
260	2.6 Flytebru - Etablere risikobasert verifikasjonsplan
261	Uavhengig integrert dynamisk analyse av flytebru
262	Evaluering av laster og lasteffekter for flytebru
263	Notat angående forankringssystemet for flytebro
264	Konseptverifikasjon av endeforankret flytebru fase 2
270	2.7 TLP - Etablere risikobasert verifikasjonsplan
271	Uavhengig analyse av TLP hengebru – fase 2
274	Konseptverifikasjon av TLP hengebru – fase 2
275	Phase 3 TLP suspension Bridge – Document review design briefs
276	Fase 3 Dokumentgjennomgang TLP hengebru
280	2.8 Kostnadsoverslag - Gjennomgang av dokumentasjon
281	FDV Modelleringsbistand
310	Skipsstøt
311	Rambøll ship impact
321	Document review phase 3 - SAFB
322,323,324,325	Independent analyses phase 3 - SAFB
326	Anchor/SSI evaluations – phase 3 - SAFB
327	Fatigue design methodology
328	K7 shear lag study BJF
410,411,412,413	4.1 Teknologikvalifisering
414	Teknologikvalifisering – lasersveising (innledende fase)
415	TQ Lasersveising - Verifikasjon
416	TQ Laser-/hybridsveising – Etablering av kvalifiseringsbasis
520	Uavhengig kontroll av skipsstøtsanalyser
521	Gjennomgang av rapporter knyttet til brann og eksplosjon for BJF
522	Gjennomgang av design basis dokumenter for Bjørnafjorden
610,615,620,625,630	BJF 2019 Reviews and Independent Analyses
650	Review of MetOcean Design Basis BJF 2019

Activity	Title
660	Sikkerhetsnivå BJF flytebruer
670	FDV modelleringsbistand fase 5
690	Undersøkelse av brukt vektkjetting fra oppdrettsanlegg
710	Gangbru Vanylven/Åfjorden
J100	Julsundet ship impact
H277	Phase 3 TLP Suspension Bridge Document Updates (Halsafjorden)
L680	Review of MetOcean DB for Langenuen
L681	Vurdering av AL hengebru over Langenuen
L682	Independent local analyses of Langenuen suspension bridge
L683	Independent global analyses of Langenuen suspension bridge
L684	Bridge pylons in steel - Langenuen

6 DOCUMENTATION RECEIVED

DNV GL has made use of NPS (Nauticus Production System) to store all received documentation from SVV and their contractors. In total there are 1277 document revisions stored in the NPS folder P22954. As noted, the main bulk of received documentation is related to Bjørnafjorden (BJF). Total number of TechDocs (TD) in NPS is 1001. Detailed overview of these received documents has been presented to SVV in monthly status reports and meetings during these 4 years. The last status report by DNV GL on this frame agreement was issued June 8th, 2020 and contains overview of all received documents.

The above numbers include the 31 technical reports (including this report) issued by DNV GL during these 4 years. See details in Section 7, DNV GL deliverables.

7 DNV GL DELIVERABLES

7.1 Technical Reports

The technical reports issued by DNV GL are shown in Table 7-1. The applied document numbering system is as set up by SVV where e.g. SBJ is related to Bjørnafjorden, HA is related to Halsafjorden and SLA is related to Langenuen. The notations C1 – C5 are related to the different phases as defined by SVV. Note that phase C4 was an internal SVV phase, hence not referred to in the table.

The last digit in the document number indicates the revision number. Typically, the first issue to the client SVV will be revision A and once SVV has accepted the report the final issue will be revision 0, or a higher number if further revisions are needed.

All the DNV GL issued documents have been uploaded to SVV eRoom. Further, the documents are stored in DNV GL Library and hence possible to retrieve in the future.

The below listed DNV GL reports are typically a mixture of document reviews and independent analyses. In addition, the list contains a guideline on technology qualification, attending FDV workshop, special studies on fatigue and the shear-lag effect and an assessment of inherent ULS safety level for BJF floating bridges. Some of the key studies/reports will be further elaborated.

Table 7-1 DNV GL issued reports/documents

Document number	Document Title
SBJ-90-C2-DNV-62-RE-001-0	Verifikasjon grunnundersøkelser Fjordkryssingsprosjektet
SBJ-90-C2-DNV-62-RE-002-0	Verifikasjon av skipsstøt
SBJ-90-C2-DNV-62-RE-003-0	Verifikasjon av designbasis dokumenter
SBJ-32-C2-DNV-62-RE-004-0	Floating bridge Risk based verification plan
SBJ-21-C2-DNV-62-RE-005-0	Suspension bridge on TLP foundations Risk based verification plan
SBJ-40-C2-DNV-62-RE-006-0	Submerged floating tube bridge Risk based verification plan
SBJ-90-C2-DNV-62-RE-007-0	Uavhengig vurdering av kostnadsestimat
SBJ-30-C2-DNV-62-RE-008-0	Concept verification of alternative: 'Curved bridge south Bjørnafjorden'
SBJ-21-C2-DNV-62-RE-009-0	Concept verification of alternative: 'Suspension bridge on TLP foundations over Bjørnafjorden'
SBJ-30-C2-DNV-62-RE-010-0	Bjørnafjord curved bridge - Independent calculation of global load effects
SBJ-90-C2-DNV-62-RE-011-0	Veileder i teknologikvalifisering for Fjordkryssingsprosjektet
SBJ-90-C2-DNV-62-RE-012-0	FDV Workshop
SBJ-21-C2-DNV-62-RE-013-0	Independent analyses of TLP suspension bridge across Bjørnafjorden
SBJ-40-C2-DNV-62-RE-014-0	Independent analyses of tube bridges across Bjørnafjorden
SBJ-40-C2-DNV-62-RE-015-0	Concept verification of tube bridges across Bjørnafjorden
SBJ-21-C3-DNV-62-RE-016-0	Phase 3-Concept verification of TLP suspension bridge
SBJ-31-C3-DNV-62-RE-017-0	Bjørnafjorden side anchored floating bridge - independent local analyses
SBJ-31-C3-DNV-62-RE-018-0	Bjørnafjorden side anchored floating bridge - independent global analyses
HA-20-C1-DNV-62-RE-019-0	Halsafjorden TLP Suspension Bridge Concept
SBJ-31-C3-DNV-62-RE-020-0	Fatigue design methodology for BJF floating bridges
SBJ-31-C3-DNV-62-RE-021-0	K7 shear lag study BJF
SBJ-32-C5-DNV-62-RE-022-0	Kvalifiseringsbasis teknologikvalifisering laser-/hybridsveising
SBJ-32-C5-DNV-62-RE-023-0	Independent Analyses of AMC Floating Bridge BJF 2019
SBJ-32-C5-DNV-62-RE-024-0	Independent Analyses of OON Floating Bridge BJF 2019
SBJ-32-C5-DNV-62-RE-025-0	Verification of AMC Floating Bridge Concepts BJF 2019
SBJ-32-C5-DNV-62-RE-026-0	Verification of OON Floating Bridge Concepts BJF 2019
SBJ-32-C5-DNV-62-RE-027-1	Assessment of inherent safety level in ULS for BJF floating bridges
SLA-22-C1-DNV-62-RE-028-0	Local FE analyses Langenuen AL bridge girders
SLA-22-C1-DNV-62-RE-029-0	Global FE analyses Langenuen AL bridge
SBJ-32-C5-DNV-40-RE-030-0	Examination of chain components
SBJ-32-C5-DNV-62-RE-031-A	Verification Summary Report E39 Bjørnafjorden (This report)

7.2 Verification Comments

Issuing and clarification of verification comments has been one of DNV GL main deliveries in this project. Typically, the workflow has been to review received documentation from the designers and issuing verification comments. This review is then typically linked to the independent analyses going in parallel with reviews and clearing of comments.

During these 4 years a total of 402 comments have been issued. Out of these, 226 are so-called AR (Action Required) comments where a response from the designer is required to close the comment. This can e.g. be achieved by a new document revision where agreed actions are included, and comment can be closed.

For some of the defined activities DNV GL issued technical reports with the verification comments included in the report itself. These comments were not included as AR & IN in NPS, but rather followed up and cleared in new revisions of the DNV GL technical reports. This implies that the number of comments issued is much higher than what is reflected in NPS. The reason for this solution was related to the need of explaining and outlining our views in more detail and thereby assist SVV and the designers in a better way.

For some of the activities, meetings were also arranged between the involved parties in order to clarify, in more detail, the comments issued.

The remaining (176) comments are so-called IN (Important Notes). These are comments that initially do not require a formal response and are per definition 'closed'. It may, however, be that some clients request their consultants/designers to respond to these comments also. In general, IN comments are considered less critical compared to AR comments.

At the time of issuing this report revision A, there are 9 open AR comments. All these are related to the recent work and activities on Langenuen aluminum suspension bridge. These open comments have been reported to SVV and in the process of being closed. It is assumed that these comments are closed when issuing the next revision of this report.

8 FOCUS ON BJØRNAFJORDEN

8.1 General

SVV has requested that this report should focus on Bjørnafjorden (BJF) as this is the most challenging crossing considered within this contract. It will also be the costliest crossing considered within this contract.

8.2 Concepts considered

8.2.1 General

A high number of concepts has been considered for BJF; typically, submerged tube bridge, TLP suspension bridge and various floating (pontoon) bridge concepts with and without transverse mooring system. DNV GL has not been directly involved in the bridge selection process but considered and commented upon the alternatives presented. However, in general DNV GL has agreed to the selections made underway.

8.2.2 Submerged floating tube bridge concept

The submerged floating tube bridge (SFTB) concept was abandoned early by SVV (Phase 2, 2017) for BJF. Still SVV wanted DNV GL to look into the conceptual documentation as the concepts could be applicable for other crossings. The verification work performed by DNV GL is documented in the two documents SBJ-40-C2-DNV-62-RE-014-0 and SBJ-40-C2-DNV-62-RE-015-0, see Table 7-1. The first document covers the independent analyses and the second is covering the document review performed.

The two tube concepts considered were the pontoon stabilized (K3) and tether stabilized (K4). See Figures 8-1 & 8-2. Aspects put forward in the DNV GL reviews were related to:

- Accidental puncture of tube and potential sinking
- Fire and explosion scenarios
- Shore approaches (especially for the pontoon alternative)
- Use of underwater rock anchors (e.g. for tethers)

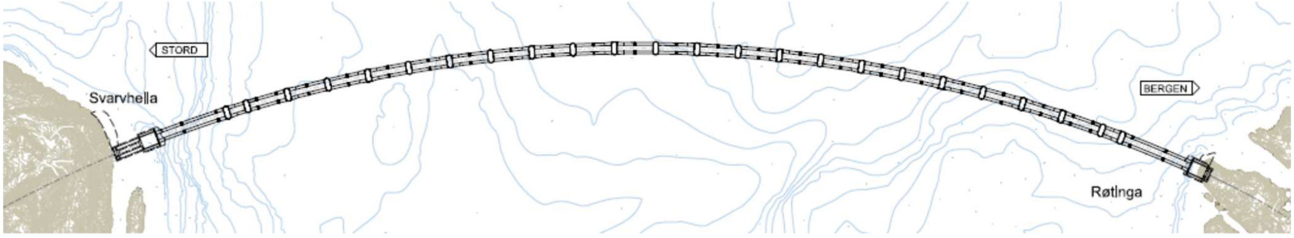

Figure 8-1 Pontoon stabilized SFTB

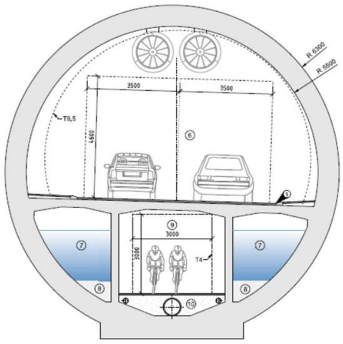

Figure 8-2 Cross section SFTB

8.2.3 TLP suspension bridge concept

In Table 8-1 a list of issued DNV GL reports in relation to the use of tethered TLP foundations for the fjord-crossings are listed. The main difference between Halsafjorden and BJF is that only one TLP foundation would be needed for Halsafjorden whereas two TLP foundations are needed for the longer BJF crossing.

Table 8-1 DNV GL reports related to TLP suspension bridges

Document number	Document title
SBJ-21-C2-DNV-62-RE-009-0	Concept verification of alternative: Suspension bridge on TLP foundations over BJF
SBJ-21-C2-DNV-62-RE-013-0	Independent analyses of TLP suspension bridge across BJF
SBJ-21-C3-DNV-62-RE-016-0	Phase 3-Concept verification of TLP suspension bridge
HA-20-C1-DNV-62-RE-019-0	Halsafjorden TLP Suspension Bridge Concept

The main conclusion from DNV GL analysis report SBJ-21-C2-DNV-62-RE-013-0 for phase 2 was that DNV GL calculated smaller characteristic design load effects than the designer, but larger individual un-combined load effects. These differences were attributed to;

- How concurrency of environmental loads was considered
- Method for estimating design load effects based on short-term statistics of extreme load effects
- Increased aerodynamic and hydrodynamic damping for combined analysis due to wind and current acting concurrent with wave loading

DNV GL observed significant differences in the individually calculated wind and wave load effects compared to designer's results. Typically, the wind load effect calculated by DNV GL for the bridge girder was 20 – 40 percent of the designer's results. For the comparison, this load effect was calculated without current, wind sea and swell. Wind sea and swell load effects calculated by DNV GL for bridge girder strong axis was 100% larger than the designer's results. In this comparison, the load effect is calculated without wind and current.

The reported differences were not investigated in detail together with the designer, but from preliminary checks it was believed that the difference in wind load effect was due to different input values for drag coefficients and the difference in wave load effect is due to differences in damping of resonant response in bridge deck lateral direction.

These differences were not pronounced in the combined characteristic design values due to the three bullets points listed above. Note that DNV GL's selection of conditions for independent calculations were based on the conditions documented by the designers such that results could be compared directly.

Recommendations given by DNV GL in the phase 2 analysis report:

- Fatigue is considered important for the design of the TLP bridge design. Designer should perform fatigue assessment during design.
- Bending response in cables, and the effect on fatigue of cables, is not included in the current modelling of the bridge. The inclusion of bending and tension dependent bending stiffness may prove important in fatigue analysis of cables close to the pylons.
- The variation of swell sea peak spectral period has been observed to have a large effect on load effect response in the bridge girder strong axis. A thorough sensitivity study for the different environmental loads and environmental load combinations was recommended.
- A combined environmental condition where current is not included should be included in future design. An increase of 20% of some characteristic design loads when current was omitted was observed by DNV GL.
- An environmental condition with only swell should be considered for future designs. The inclusion of turbulent wind and current increases damping and reduces possible resonant response from swell conditions.

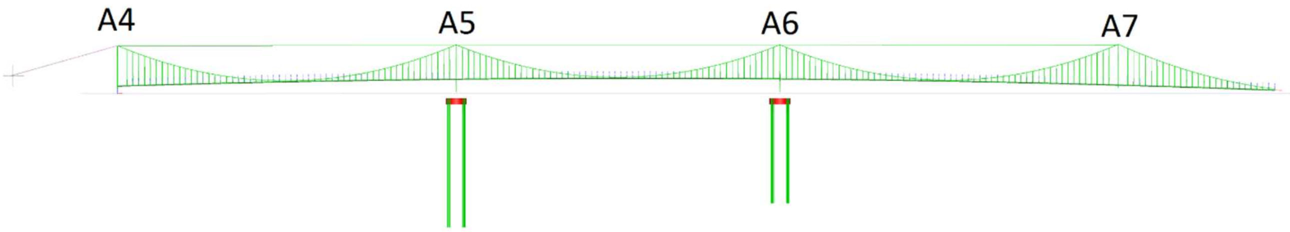

Figure 8-3 DNV GL analysis model of TLP suspension bridge across BJF

The phase 3 DNV GL report (SBJ-21-C3-DNV-62-RE-016-0) was issued in the winter/spring of 2018 and was related to document review of the BJF multi-span TLP suspension bridge. The report addressed the most important aspects found during verification work and can be summarized as follows:

- The TLP suspension bridge concept is more difficult to analyze than ordinary bridges. Even if considerable efforts are made in the conceptual design as presented by the phase 3 received documents there is in DNV GL opinion larger uncertainties related to this concept than for other bridge concepts.
- Change of design parameters during the design process may significantly change the calculated stresses, resulting in need for increased steel weight of the considered structural elements. A further increase in steel weight will require new requirements to buoyancy. This may further increase the loads. Thus, the structural behavior of the bridge is sensitive to the mass and stiffness of the different parts leading to difficulties for the design process to converge to a sound concept. This implies that the design process may easily enter a design spiral (often typical for offshore TLPs). Therefore, there is need for significant concept developments to establish a reliable cost and schedule estimate for this concept.
- In the view of DNV GL there is so far put too little emphasis on checking the dynamic effects from the loads on the fatigue resistance of the various structural elements. It is expected that the design of a structure that is floating will in large extent be governed by its fatigue strength. The structural elements of concern are the main and top cables, the bridge girder, and the pylon supported on the two TLP structures/foundations.
- Further, some concerns were also raised in relation to geotechnical aspects (tether suction anchors) and temporary phases (installation of the bridge).

8.2.3.1 Halsafjorden

The assessment of the Halsafjorden TLP suspension bridge was performed by DNV GL in winter/spring 2018. This was a high-level assessment of a concept with one tethered TLP foundation midfjord and fixed pylon on land in each end. Limited documentation was available at the time and documentation from BJF had to be considered as a supplement. See concept illustration in Figure 8-3.

Some of the main issues that were put forward by DNV GL in the review:

- The concept is rather complex to analyse in terms of structural responses (two fixed and one moveable pylon)
- Challenging to determine the responses in top and main cables
- Fatigue/Design Fatigue Factors
- Bending of pylons due to moveable TLP foundation
- Use of and response in dampers
- Complex installation
- Somewhat optimistic bridge girder dimensions (plate thicknesses)

Comments issued by DNV GL were responded to by the designers and all is included in the DNV GL report (HA-20-C1-DNV-62-RE-019-0).

Figure 8-4 Illustration of TLP suspension bridge across Halsafjorden

8.2.4 Bjørnafjorden floating (pontoon) bridge concepts

The floating (pontoon) bridge concept has been a front runner during this concept screening phase. This is a proven concept with 25 – 30 years of operational experience from Bergsøysundet and Nord Hålogaland floating (pontoon) end supported bridges. The scale is, however, totally different with only 20% – 25% compared to the 5 km long BJF bridge.

Table 8-2 presents the key reports issued by DNV GL for this concept.

Table 8-2 DNV GL reports related to floating (pontoon) bridges

Document number	Document title
SBJ-30-C2-DNV-62-RE-008-0	Concept verification of alternative: 'Curved bridge south BJF'
SBJ-30-C2-DNV-62-RE-010-0	BJF curved bridge - Independent calculation of global load effects
SBJ-31-C3-DNV-62-RE-017-0	BJF side anchored floating bridge - independent local analyses
SBJ-31-C3-DNV-62-RE-018-0	BJF side anchored floating bridge - independent global analyses
SBJ-31-C3-DNV-62-RE-020-0	Fatigue design methodology for BJF floating bridges
SBJ-31-C3-DNV-62-RE-021-0	K7 shear lag study BJF
SBJ-32-C5-DNV-62-RE-023-0	Independent Analyses of AMC Floating Bridge BJF 2019
SBJ-32-C5-DNV-62-RE-024-0	Independent Analyses of OON Floating Bridge BJF 2019
SBJ-32-C5-DNV-62-RE-025-0	Verification of AMC Floating Bridge Concepts BJF 2019
SBJ-32-C5-DNV-62-RE-026-0	Verification of OON Floating Bridge Concepts BJF 2019
SBJ-32-C5-DNV-62-RE-027-1	Assessment of inherent safety level in ULS for BJF floating bridges

8.2.4.1 Curved bridge south

The two first reports (SBJ-30-C2-62-RE-008/010) were issued by DNV GL in 2017 and contained a document review and independent analyses of the end supported bridge concept. At this point in time the bridge was curved towards south/west and had no supporting side mooring system. The document review addressed the following key aspects:

- It was recommended to establish an environmental (metocean) design specification that would be similar for the various concepts. This specification should be formulated such that it will provide conservative results for the ultimate strength design and for the fatigue design.
- The design should focus on the fatigue strength also in the conceptual stage.
- **The representation of a Vierendeel girder with as a single beam model needs to account for the increased flexibility by adjusting the shear stiffness and also to consider the bending stresses caused by the Vierendeel bending moments.**

- The method of applying combination factors between different stress-resultants to obtain design responses seems not satisfactory substantiated.

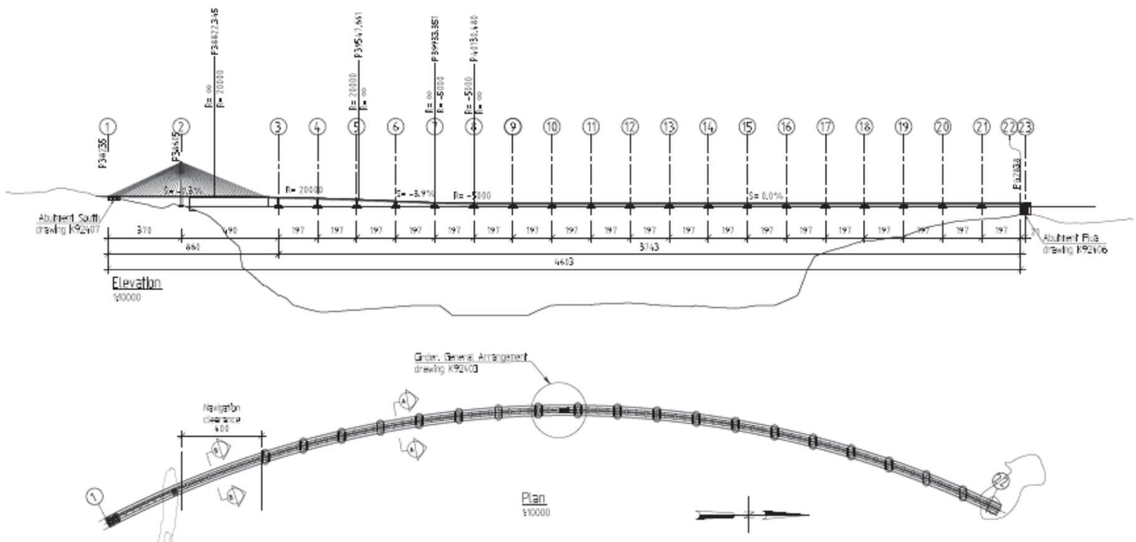

Figure 8-5 Phase 2 overview of concept plan and elevation

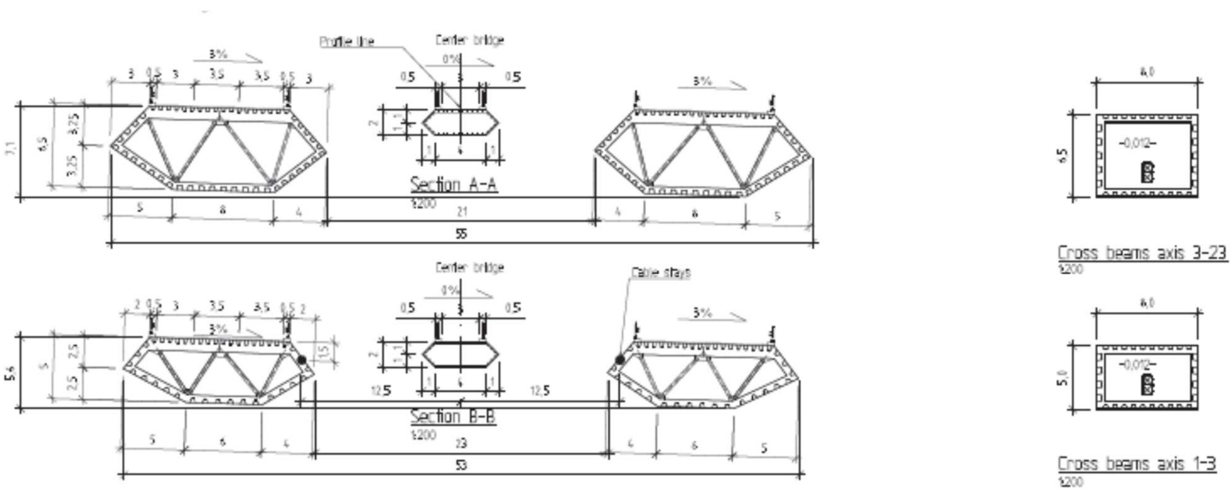

Figure 8-6 Phase 2 cross-section of bridge girder and cross beams

The primary objective with DNV GL independent analyses were to perform independent load effect analyses, estimate design load effects and compare with designer's calculations. Further, to report any potential gross errors in the methodology applied by the designer and designer's estimates of the design load effects.

DNV GL independent calculations generally revealed smaller design load effects than designer's calculations. This difference was mainly attributed to differences in:

- How concurrency of environmental loads was considered
- Method for estimating design load effects based on short-term statistics of extreme load effects

Note that DNV GL's selection of conditions for the independent calculations was based on the conditions documented by the designers such that results could be compared directly.

For the next design phases DNV GL recommended the designer to consider fatigue as well as other potentially onerous load combinations for ULS such as e.g. uneven wind field along the bridge girder.

8.2.4.2 Side moored straight floating bridge

In phase 3, 2018 several verification reports (SBJ-31-C3-DNV-62-017/018/020/021) were issued by DNV GL. With the introduction of a transverse mooring system along the bridge, the BJF bridge was proposed made straight, as shown in Fig. 8-7.

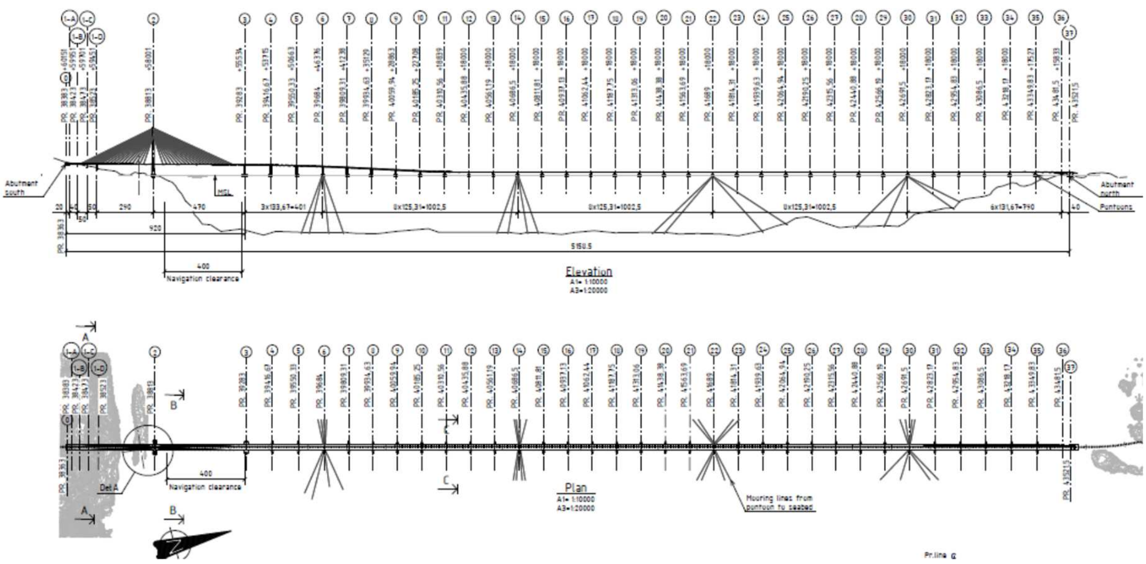

Figure 8-7 Side anchored straight bridge

In report SBJ-31-C3-DNV-62-RE-017-0, several locations along the bridge were analyzed for traffic loading, both locally between pontoons and the localized effect of a wheel bending the plate and stiffeners between transverse frames. Typically, stress transfer factors between global load effects and stresses were established for 5 locations in several cross-section types. SCFs were established for 7 hot spots in the connection between stiffeners and a transverse frame for a section (F1). It was shown that for global loads the worst hot spot was the buttwelds in the bridge deck and bottom plate.

During the work with the stress transfer factors it was found that the F1-F3 type of cross sections were not fully effective against weak axis bending due to **shear lag** effect. This would increase the global stresses due to weak axis bending significantly. Thus, it was recommended to add longitudinal webs to obtain a cross section with neglectable shear lag effect.

The calculated fatigue lives due to global bending from traffic gave fatigue lives above 600 years at all studied cross sections. Thus, the fatigue damage due to global bending from traffic alone was acceptable. However, when the global fatigue damage was combined with fatigue damage from tidal variations the lowest calculated fatigue life in the north end of the bridge was 124 years.

The method for combining fatigue damage from two different response processes from DNVGL-RP-C203, was investigated by comparing the combined response with rain-flow counting (RFC). Fatigue damage was calculated with the use of RFC on time series with both tidal variations and traffic. The results showed good correspondence between RFC and the method from DNVGL- RP-C203.

Stress cycles due to direct wheel loads were calculated for both the transverse frame and the deck plate and stiffeners between the transverse frame. High local stresses were found at the cut out around the trapezoidal stiffeners and at the cope holes towards the bridge deck. The stresses would be significantly reduced by designing a stiffener connection without cope holes and by carefully designing the cut-out around the stiffener. Guidance for stiffener connections is provided by the US Federal Highway Administration and recommendations on design of stiffener connections without cope holes are given in NS-EN-1993-2 informative Annex C.

In the deck plate between transverse frames, the most utilized area (hot spot) with respect to fatigue due to direct wheel loads was found to be the buttweld in the bridge deck. This is an important hot spot as all response processes contribute to the damage at this location. Calculated fatigue life from wheel load alone was found to be below 100 years. To improve the results, it was recommended to refine the analysis by accounting for the asphalt’s effect on the wheel load pressure. It was further recommended to increase the thickness of the deck plate with minimum 2 mm in accordance with the recommendations in NS-EN-1993-2 informative Annex C.

Two different long-term distributions of tidal variations were analyzed, and the fatigue damage was calculated. The first distribution assumed a constant tidal amplitude equal the Mean High Water (MHW) amplitude. In the second distribution, the tidal amplitudes were divided into 3 blocks. The three blocks contained equal number of cycles and represented the amplitudes corresponding to Mean High Water Spring (MHWS), MHW and Mean Low Water Neap (MLWN), respectively. The result showed that the calculated fatigue damage from tidal variation alone were reduced with about 20 % with the three-block distribution. Due to the obtained difference and the significance of fatigue due to tidal variations towards the abutments, a more refined long-term distribution of tidal variations should be developed for the final design.

A different method for combination was proposed and tested by combining the calculated fatigue damage from traffic and tidal variations and comparing with RFC. The results showed that the proposed method performed worse compared to the method given in DNVGL-RP-C203. Thus, further testing and refining of methods regarding combining damage from different response processes was recommended by DNV GL.

DNV GL report SBJ-31-C3-DNV-62-RE-018-0 documents the independent global TD analyses for the Phase 3, BJF side anchored straight floating bridge. The primary objective was to check that the conceptual design was sound and that the concept could be realized according to the designer's plans. The independent analyses were confined to check the capacity of the bridge girder and the mooring lines.

The global analyses were carried out without accounting for the shear lag effects of the bridge girder. This is similar to what was made by the designer and made global analyses results comparable. A series of sensitivity analyses were carried out to give further insight in the behavior of the bridge.

In general, the results for the 100-year environmental conditions found in the global analyses correspond well with the results from the designer. There was, however found large differences in the strong axis bending moment. This was subject to further investigations together with SVV and the designer. DNV GL had a theory (small rotations along the bridge) about the reason for this, but no firm conclusion was made.

Checks of the ultimate limit state shows exceedance of the criteria for large parts of the low bridge. This is mainly due to shear lag effects that make the cross-section less effective for weak axis bending.

A simulation of an alternative design was made by DNV GL where reductions from shear lag were excluded. This represents a case where, for instance, additional webs in the longitudinal direction are introduced, without changing the steel area, although this may be difficult to achieve in practice. This simulation showed that the cross-sections where the capacity cannot be proven were limited to a few, and that a minor increase of dimensions will make the bridge girder meet the requirements.

Calculated fatigue damage from traffic loads was analyzed and reported by DNV GL. It was found that the bridge deck plate was too thin and that the current details for the stiffener to crossbeam connection needed to be improved.

Calculated fatigue damage due to tidal variations and traffic at the end span at the north end was larger than allowed mainly due to the shear lag effects present for the cross-section type F1 located in mid span between pontoons.
Calculated fatigue damage from environmental loads was too large for the cross-sections that are subjected to large effects from shear lag. If the cross-section was modified to minimize shear lag effects, fatigue loads from environmental loading could be resisted. If the plate thickness in the bridge deck is increased as proposed above, it is predicted that adequate fatigue life can be computed even for combined effects from environmental loads, tidal variations and traffic loads.

It was found in the analyses carried out that the fatigue damage calculated was sensitive to the assumptions made and that the combination of fatigue damage from various sources add to the complexity and consequently the accuracy of the calculations.

The calculated maximum mooring line tensions were comfortably below the required safety factor of 2.2. The calculated minimum fatigue life is slightly above the required 1000 years, which correspond to 100 years of service life with a design fatigue factor (DFF) of 10.

Marine growth increases the loads on the mooring system and must therefore be considered for its ULS and FLS calculations. Based on the performed sensitivity analysis the fatigue life of the mooring system may not be sufficient, although calculated fatigue life can be improved with minor changes in the mooring system in a detailed design phase. As an alternative, the not complying lines could be replaced once during the bridge's operational life.

The combination of safety format from EC3, and the S-N curves from DNVGL-RP-C203 may be conservative. In Eurocode the S-N curves have a fatigue limit while the S-N curves from DNVGL-RP-C203 have not. Thus, with small stress ranges the S-N curves from DNVGL-RP-C203 will give higher calculated damage compared to Eurocode. This combined with the material factor used in Eurocode may give conservative results.

For the reasons described above the fatigue calculations performed for this bridge must be more refined compared to other bridges. In addition, the damage contribution from each response process must be minimized as much as practical possible. Presently the methods for combination of fatigue damages from different response processes work well for processes with significant difference in total number of cycles. Traffic and tidal variations can be combined with well-established methods with sufficient accuracy. The combination damage from traffic loads and environmental loads needs a more refined method.

Some recommendations regarding improvement of the fatigue design and how to perform more accurate fatigue calculations are given below:

Design changes:

- All cross-sections should be made with sufficient webs to avoid ineffective cross-sections for weak axis bending.
- Increase plate thickness in the bridge deck to a minimum of 16 mm.
- Improve stiffener to crossbeam connection details.
- Shore entry at the north end should be developed further before deciding on design.

Other measures:

- Specify Fatigue Load Model 4 or 5 from NS-EN 1991-2:2003, for future fatigue checks.
- Establish long term distributions for tidal variations.
- The safety format and safety factors may need to be re-established. Combination of Eurocode and offshore standards may prove necessary and detailed procedures should be established.
- Establish synthetic (defined) load stories for traffic to be able to combine damages with other damaging processes.
- Further investigate the differences in the analysis models which lead to much larger strong axis bending moment of the bridge girder in SIMO-RIFLEX than in the design analyses. This comparison has started but it is not concluded at this revision of the report.

  Comment June 2020: This issue was investigated for several months together with SVV and the designer without reaching a firm conclusion. DNV GL had a theory about the small rotation of the bridge together with axis systems could explain (calculations made) this difference. DNV GL has used the same software (SIMO/RIFLEX) for all independent analyses on this contract and has a lot of confidence in the software and used it in multiple projects (floating structures, TLP tether systems, riser systems, mooring systems, pipelines, offloading lines) for several decades.

8.2.4.3 Fatigue design methodology

The objective with DNV GL report SBJ-31-C3-DNV-62-RE-020-0 was to develop a methodology to calculate fatigue damage considering the effect of combined load response from environmental loads, traffic loads and tidal variations. By environmental loads it is meant loads from wind sea, swell and wind. Various topics related to fatigue damage calculations from traffic were studied. The following results from this work are listed:

- Design fatigue model 4 according to NS-EN-1991-2 is proposed to be used for future design developments. Load category and Load type to use with this model has been selected. These selections will imply an increased fatigue loading from traffic compared with what was used in the DNV GL independent analyses.

- The fatigue load model should be further developed to give details that are not given in NS-EN-1991-2 e.g. amount of traffic in opposite direction and in second line.
- The background for the S-N curves in EN 1993-1-9 and DNVGL-RP-C203 has been presented. EN1993-1-9 is typically used for fatigue design of land-based structures while DNVGL-RP-C203 is used for offshore structures. The differences between the S-N curves and the design formats in the two standards have been described.
- For purpose of fatigue design of floating bridges, it is assessed that DNVGL-RP-C203 is more complete with respect to S-N curves for marine environment and this standard includes a fatigue design procedure to be used with calculated hot spot stresses from finite element analysis. Therefore, this document is recommended used for further fatigue assessment of floating bridges.
- The FLS safety levels in EN 1993-1-9 and DNVGL-RP-C203 standards have been compared. DFFs combined with S-N curves in DNVGL-RP-C203 that correspond to the safety format and the S-N curves in EN 1993-1-9 have been calculated for typical long-term stress range distributions for floating bridges from environmental loads and traffic loads. Environmental loads are assumed loads from wind sea, swell and wind.
- DFFs that meets the intended safety level of EN 1993-1-9 for different parts of a floating bridge have been proposed.
- Combinations of long-term stress cycles from environmental loads and traffic loads have been assessed. It is found that the stress ranges from environmental loads and traffic loads can be added together without significant conservatism before the fatigue damage is calculated from a relevant S-N curve and number of stress cycles. This applies also to the stress cycles due to tidal variations in combination with stress cycles from environmental action and traffic load.
- A methodology to calculate fatigue damage considering the effect of combined load response from environmental loads, traffic loads and tidal variations has been proposed.
- The proposed fatigue design procedure is based on numerical analysis and considered to be accurate for purpose of concept development as well as for a detailed design of a floating bridge.
- It is proposed that guidance is developed to determine bridge deck details. These details will be governed by analysis of fatigue damage from wheel pressures and the problem will be similar for different bridge concepts. However, presently adequate analyses results, as basis for this are lacking.
- DNV GL independent analyses of the proposed design of side-anchored floating bridge concluded that the fatigue strength of the bridge deck details was insufficient. With Fatigue load model 4, as proposed in this study, the fatigue loading from traffic will increase and consequently the fatigue damage will be increased compared with what was reported in DNV GL independent analyses.

8.2.4.4 Shear Lag study

The objective of DNV GL report: SBJ-31-C3-DNV-62-RE-021-0 K7 shear lag study BJF, was to study the effects on stiffness and strength when additional longitudinal webs are introduced. Additional webs help to increase the effective width of the box girder flanges when exposed to weak axis bending. The study was based on the methods given in NS-EN 1993-1-5.

It was found the stresses from weak axis bending could be reduced by a factor of up to 5.5 by introduction of three additional longitudinal webs. Also, the stiffness of the bridge about its weak axis were increased by the proposed modification.

8.2.4.5 Concept selection BJF floating bridge

In the period summer 2018 up to spring/summer 2019 a comprehensive amount of work was performed for SVV in phase 5 by two design groups; AMC and OON. The main objective was to end up with a final concept for further design development. Both groups considered 4 different floating bridge alternatives, these were:

K11 – Curved, end-anchored floating bridge in accordance with phase 4 of the project

K12 – Curved, end-anchored floating bridge with supplementary side moorings

K13 – Straight, side anchored floating bridge

K14 – 'Straight' S-shaped, side anchored bridge

Both design groups suggested to go forward with the K12 alternative and DNV GL agreed to this choice. This alternative was also subject to independent TD simulations by DNV GL. Figs. 8-8 - 8-11 show the AMC and OON K12 alternatives.

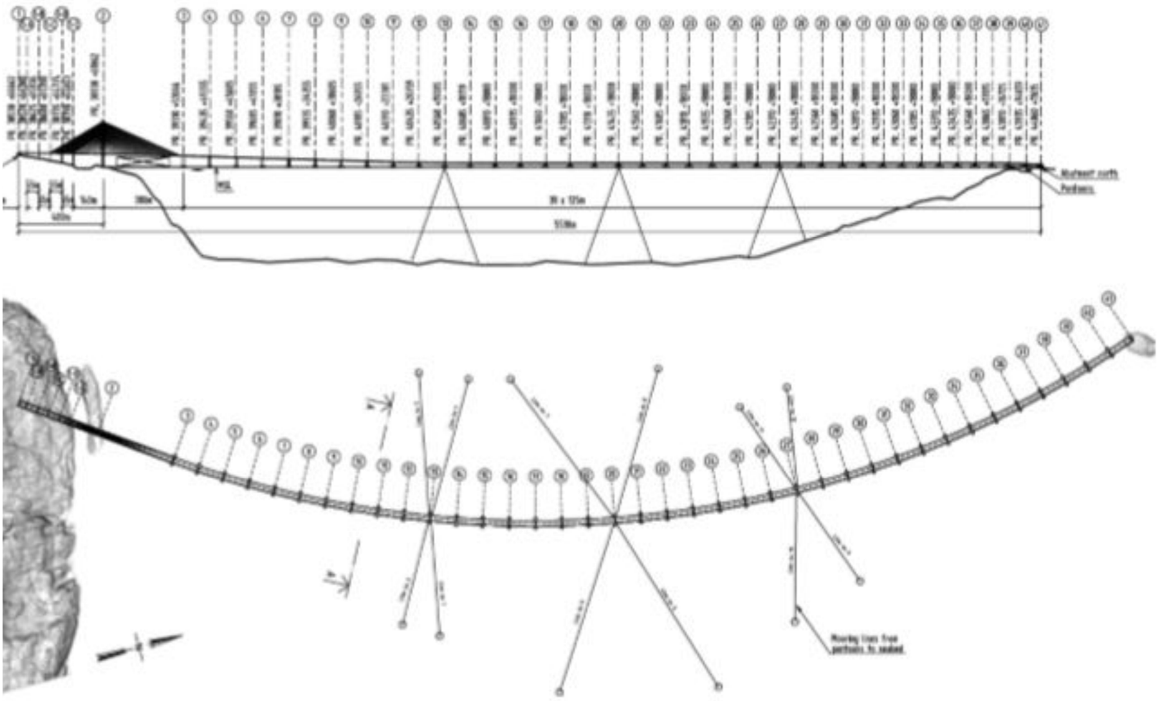

Figure 8-8 AMC chosen alternative K12

Figure 8-9 AMC K12 concept, as seen from north end

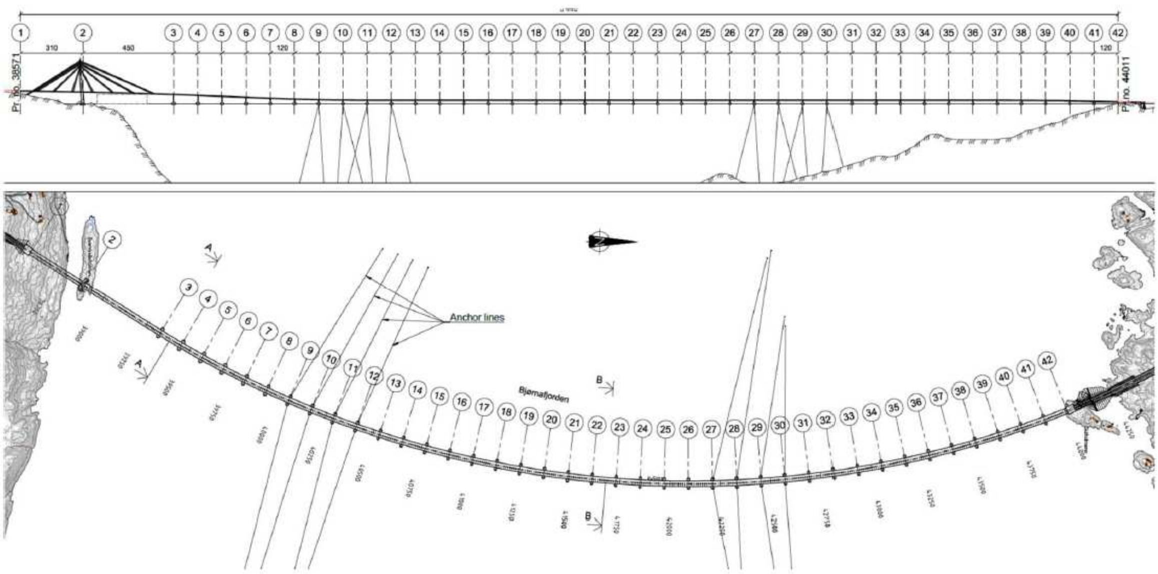

Figure 8-10   OON chosen alternative K12

Figure 8-10   OON concept, seen from north west

DNV GL had a large scope related to this phase in almost parallel with the two design groups. The work performed by DNV GL included both document reviews and independent analyses as reflected in the four reports SBJ-32-C5-DNV-62-RE-023/024/025/026-0.

The review of the AMC K12 bridge documentation by DNV GL concept did not reveal any major deficiencies that could impact the feasibility of the project. However, some points were raised that could have moderate impact on the cost and the schedule, typically:

- The strength of the bridge girder is not fulfilling the imposed actions at the tower and at the North end of the bridge and the need for reinforcements are identified. However, the bridge girder dimensions at these locations are already increased compared with the typical crossection and further strengthening may lead to more costly details especially since also fatigue loading is high. It may be considered to allow for steel with strength higher than premised in the design specification in order to solve this design task.
- The selected design has not been proven for the specified energies to boat impacts. Capacity to resist half the energy is shown to result in damages that will not lead to loss of the bridge. The bridge will be able to resist larger energies than half the specified for many scenarios, but not at its most vulnerable positions. Even if the high boat impact energies imply large damages to the pontoon, the column and the bridge girder, it is judged that the probability of total loss of the bridge is small. Consequently, the robustness of the K12 bridge concept is considered to be good in this respect. If an ALARP philosophy is followed it is judged that the present design, that has capacity to resist 50% of the impact energy, can be regarded as reasonable.
- It is noted that it is difficult to document enough fatigue life along the longitudinal stiffeners due to local traffic loads without including the stiffness effect of the asphalt layer. It is agreed that one may consider the stiffness of the asphalt layer for this stress direction to avoid a conservative design. It is judged that future technology developments on load modelling, structural detailing and analyses the cost to meet design requirements can be limited.
- The concept for fabrication and installation as presented in this phase is considered feasible. However, fabrication and installation of the bridge are at this stage described on a high level. Consequently, DNV GL consider the basis for cost and schedule estimates as very uncertain for the construction phase.

Several recommendations were raised by DNV GL for the AMC concept:

- Review the ship impact methodology to account for the reduced probability for certain impact scenarios and to consider application of ALARP for cases with large cost consequences.
- Traffic model and definition of characteristic traffic loads. The traffic model may be governing for the geometry at significant hot spots and the definition of the characteristic load may influence on the required Design Fatigue Factor.
- The transfer of dynamic forces in the longitudinal direction of the bridge girder leads also to hot spots in the trapezoidal sections at the welded connections at the cut-outs in the transverse girders. It is important to document enough fatigue life at all these hot spots due to the large number of connections between the longitudinal stiffeners and transverse frames.
- It is expected to be simpler to fabricate connections with long fatigue lives using other types of stiffeners than trapezoidal sections such as HP sections. Therefore, one may

check if these stiffeners can be efficiently used in other areas than below the traffic loaded bridge plate.

- The calculation methods related to fatigue damage in the deck plate should be calibrated as far as possible with experience. There are also hot spots at the connections between the longitudinal trapezoidal sections and the transverse frames that needs to be further assessed with respect to traffic loads. Also, here the stiffness of the asphalt layer may be considered accounted for in the fatigue assessment.
- Assembly of the high floating bridge. Technical challenges are related to jacking of the bridge girder, notably stability of the jacking towers, accidental conditions etc. Maneuvering and sea room at the proposed assembly location should also be considered further.
- Towing and installation of the complete floating bridge are complicated marine operations, and further planning is required.
- The locking system for the construction joints in the main bridge girder must be engaged quickly (i.e. within the weather window) during the installation of the main floating bridge, and thereafter be able to transfer the sectional bridge girder forces until the connections have been welded. The documentation regarding this is immature, and the locking system should be further developed.
- Local reinforcements and temporary steel are required to transfer loads during construction/assembly. Further detailing and to clarify possible consequences of remaining temporary steel on in-place (fatigue) stresses are recommended.
- It is recommended to further develop the metocean design basis for the next phase in the development of the BJF bridge. The analyses of the K12 concepts from AMC (and OON) have shown that the dynamic response in the bridge is sensitive to the current speed; a large current speed will reduce the response due to the increased damping. It is therefore necessary to define the current speeds and directions that shall be combined with extreme wind and wave conditions and also FLS conditions. For the FLS analyses it should also be specified how to combine wind sea and swell. Analyses so far by the designers and DNV GL have been performed without any wind load on the bridge girder in longitudinal direction. It should be investigated if this simplification is acceptable.

The independent analyses of the AMC concept by DNV GL concluded with the following:

- The calculated stresses exceed the ULS capacity of the box girder at Axis 2 (tower) and need to be reinforced. At the North end the capacity is at the limit and reinforcements may be needed. This agrees with the checks done by the designer. The rest of the bridge girder satisfy the specified requirements.
- The independent analyses carried out by DNV GL determines the contribution to fatigue damage from environmental loads in the bridge girder. The results from the screening analysis show a minimum calculated fatigue life of 482 years. This number should be reduced due to the local stress increase. A reduction similar could be expected that will bring the fatigue damage from environmental loads close to the required life of 250 years. The contributions to accumulated fatigue damage from traffic and tidal variation were not part of the independent analyses by DNV GL. The contributions will add to the damage only at certain details in the bridge. Tidal variation will only lead to fatigue damage close to the ends and traffic will predominantly give fatigue damage in the bridge deck. However, the fatigue loading as determined by DNV GL show that it should be expected that in certain areas details as assumed in the fatigue screening with SCF of 1.5 and SN-curve D may not be allowed even from environmental actions alone.

- The responses in the mooring system give a safety factor well above the requirement of 2.2. The calculated fatigue life for the top chain is just above the requirement of 50 years design life and DDF of 10, while the bottom chain goes below 100 years design life and DDF of 10. These results are with a SCF of 1.15, which may be conservative.

The review of the OON K12 bridge documentation by DNV GL did not reveal any major deficiencies that may impact the feasibility of the project, but there are uncertainties for certain items that may affect the cost and schedule as listed below:

- There are considerable fatigue loading on the bridge both from environmental loads and traffic. Fatigue capacity checks are carried out for typical details along the bridge. The most fatigue loaded details are not designed to sufficient detail and therefore the calculated fatigue life is uncertain. Furthermore, stress concentrations due to shear lag and changes in cross sections are not accounted for. There are assumed favorable fabrication methods leading to little margins for deviations that may be experienced during construction. The need to design and fabricate fatigue loaded structures is more costly than predominantly static loaded structures. The current design needs to be improved to meet the fatigue requirements, but with future technology developments the cost of these improvements can be reduced.
- The effect of the local traffic has been considered together with the effect of the environmental response for fatigue assessment of details subjected to stress ranges in the longitudinal direction of the bridge. Based on this work a plate thickness equal 14 mm has been decided. However, so far, a fatigue assessment of the dynamic stresses transverse to the longitudinal stiffeners has not been reported. Based on experience from other projects and literature from other countries it is expected that this condition may be governing for the traffic on the deck with heavy traffic. It is expected that the requirement to traffic model will be revisited before a further design phase is started and based on this it is recommended that fatigue analysis for stress ranges transverse to the longitudinal stiffeners are performed before a recommended plate thickness in the bridge deck is decided.
- The selected design has not been proven for the specified energies to boat impacts for the bridge end at the North abutment. Furthermore, energy absorptions from ship impacts against the pontoon is assumed to be taken by plastic deformations in a concentrated zone in the columns but with extensive penetrations of the ships bow into the pontoon structure. It is judged that design development on the basis of the specified energies resulting in limited damages that can be repaired will be costly and that it should be considered to follow an ALARP philosophy for the development of the design. It is judged that the probability of total loss of the bridge is small even with considerable damages to pontoons and bridge girder and the robustness of the bridge is considered to be good against total loss.
- The mooring design analyses have been based on the linearized quasi-static stiffness. This means that the mooring loads will be under-predicted, both for ULS and FLS. However, loads the in the bridge girder will be over-predicted.
- The concept for fabrication and installation as presented in this phase is considered feasible. However, fabrication and installation of the bridge are at this stage described on a high level. Consequently, DNV GL consider the basis for cost and schedule estimates as very uncertain for the construction phase.

A number of recommendations were also raised by DNV GL for the OON concept:

- In the fatigue analyses very low stress concentration factors have been assumed for the butt welds in the bridge girder. This will require special attention to other hot spots such as where the longitudinal trapezoidal sections are welded to the transverse frames. This relates to stresses in the longitudinal direction of the bridge due to the global response and also to local stresses resulting from the traffic load on the bridge. Due to a significant number of welded connections between the longitudinal stiffeners and the transverse frames it is recommended to investigate this further in the next project phase to arrive at optimal connections that can be used for documentation of fatigue.
- Calibration with experience from similar structures is recommended to avoid a conservative design. For this purpose, the stiffness of the asphalt layer may be included in the fatigue assessment for transverse stresses due to local traffic loads.
- It is noted that trapezoidal sections are used as stiffeners in general. It is assessed that open stiffeners such as bulb section may be easier to weld to the transverse frames without large stress concentrations. Therefore, it is questioned if other types of stiffeners than trapezoidal sections should be used in areas away from the traffic loaded deck plates. This consideration applies both to the bridge girder and also to the columns where it is expected to be a challenge to achieve good details by using trapezoidal sections as plate stiffeners. However, due to limited drawings of details it is not clear how acceptable details can be achieved at important connections by using trapezoidal sections. Thus, development of drawings showing significant details and welded connections should be given the highest priority in a further concept development. This is also in line with the recommendations for further work by the designer.
- It is noted that the wind response is quite sensitive to the statistical variations of the wind field characteristics. It is recommended to establish load cases which consider un-favorable combinations of wind field parameters.
- Towing and installation of the complete floating bridge are complicated marine operations, and further planning is required.
- The locking system for the construction joints in the main bridge girder must be engaged quickly (i.e. within the weather window) during the installation of the main floating bridge, but the documentation regarding this is immature. The locking system should be further developed.
- Local reinforcements and temporary steel are required to transfer loads during construction / assembly. Further detailing and to clarify possible consequences of remaining temporary steel on in-place (fatigue) stresses are recommended.
- It is recommended to further develop the metocean design basis for the next phase in the development of the BJF bridge. The analyses of the K12 concepts from OON (and AMC) have shown that the dynamic response in the bridge is sensitive to the current speed; a

large current speed will reduce the response due to the increased damping. It is therefore necessary to define the current speeds and directions that shall be combined with extreme wind and wave conditions and also FLS conditions. For the FLS analyses it should also be specified how to combine wind sea and swell. Analyses so far by the designers and DNV GL have been performed without any wind load on the bridge girder in longitudinal direction. It should be investigated if this simplification is acceptable.

The independent analyses of the OON concept by DNV GL concluded with the following:

- The ULS capacity made as a von-Mises stress check is exceeded at Axis 3 to 9 and close to the abutment North. Independent buckling checks are not carried out, but it is expected that reinforcement at these cross-sections will also make the buckling capacity acceptable. The stress check is based on beam theory and that stress increase due to local stiffening and shear lag is not accounted for. The available free movement space for the bridge girder at the tower is not sufficient to avoid contact from the bridge girder into the tower for ULS loads. The risk of clash will be drastically reduced by narrowing the girder to the width without the wind nose.
- The independent fatigue analyses carried out by DNV GL determine the contribution to damage from environmental loads in the bridge girder. The results from the screening analysis show a minimum fatigue life of 148 years. This number should be reduced with the local stress increase. A reduction similar to the example given in the report could be expected that will bring the fatigue damage from environmental loads significantly below the required life of 250 years. The contributions from traffic and tidal variation were not part of the independent analyses by DNV GL. The damages will add only at certain details in the bridge. Tidal variation will only lead to damage close to the ends and traffic will predominantly give damage in the bridge deck. However, the fatigue loading as determined by DNV GL seems to be above the required capacity for large part of the structure.
- In regard the mooring system, the size of the bottom chain needs to be increased and this can be included at a small cost increase. Thereby, the strength of the polyester lines will become governing with a safety factor just above the requirement. The fatigue in the bottom chain is below the requirement, but this will be changed if the dimension of the bottom chain is increased due to the strength requirement. The increased dynamic loads in mooring lines may also affect the out-of-plane bending of the top chain. This should be further evaluated.
- The designer has used quasi-static stiffness for the mooring lines, while DNV GL has used dynamic stiffness, which is more appropriate. This results in larger dynamic line tensions than the designer. Apart from the small effect on the eigen periods, the use of quasi-static stiffness is probably slightly conservative with respect to the response in the girder. Otherwise, the analysis results are generally in line with designer’s results.

8.2.4.6 BJF floating bridge inherent ULS safety level

This study was initiated by SVV after the verification work for phase 5 had been completed by DNV GL in the fall of 2019. A lot of initial discussion with SVV and agreeing on the scope of work was done before the activity was approved by SVV and actual work could be initiated.
Several alternative structural reliability analysis (SRA) methods were investigated and documented by DNV GL and results were subsequently discussed with SVV and their specialists. Final revision (rev. 1) of this report is planned to be issued end of June 2020. How/if this study/work will be implemented in the further development of the BJF floating bridge will be up to SVV to decide.

9 LANGENUEN ALUMINUM SUSPENSION BRIDGE

During the last half year of this contract a lot of focus has been on the possible use of aluminum in a 1200 m long suspension bridge across Langenuen. This is also an important crossing (part of Hordfast) along E39 between Stavanger/Haugesund and Bergen and steel alternatives are already considered available. Documents issued by DNV GL are shown in Table 9-1. Activities included document review of the design documents and independent local and global analyses.

A separate review was also made related to the possible installation of a one-piece steel pylon from the seaside. This review focused mainly on marine operations.

Table 9-1 DNV GL reports issued related to Langenuen

Document number	Document title
SLA-22-C1-DNV-62-RE-028-0	Local FE analyses Langenuen AL bridge girders
SLA-22-C1-DNV-62-RE-029-0	Global FE analyses Langenuen AL bridge

Two different (panel & plate) cross-sections were analyzed by DNV GL and the global dynamic wind analyses revealed responses comparable to those documented bythe designer. The local FE analyses did however reveal challenges related to fatigue caused by traffic loading. Subsequent to these analyses there has been made changes to the bridge girders to improve the fatigue lives due to traffic loading. This is ongoing work and will not be commented upon further herein.

10 REFERENCES

/1/ Rammeavtale (15/255967) for rådgiving, kontroll og kvalitetssikring for fjordkryssingsprosjektet. Statens vegvesen, Region vest.

About DNV GL

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