Appendix to report:

SBJ-33-C5-OON-22-RE-017
DESIGN OF BRIDGE GIRDER

Appendix title:

APPENDIX A – SHEAR LAG STUDY

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CONCEPT DEVELOPMENT FLOATING BRIDGE E39 BJØRNAFJORDEN

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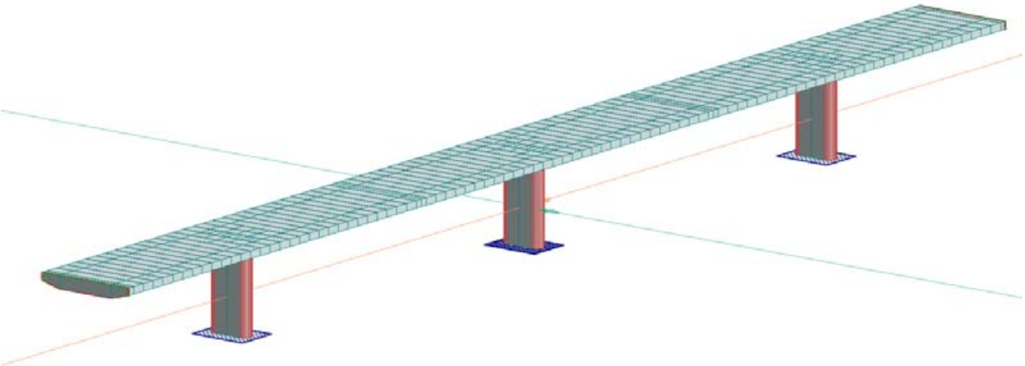
1 SHEAR LAG STUDY

Shear lag effect is important to consider for this type of structure. All stresses from global analyses are reported based on full general cross section, and do neither compensate for shear lag effect, nor include strengthening of the cross section at supports. Shear lag effect will increase the stress and strengthening will reduce the stress.

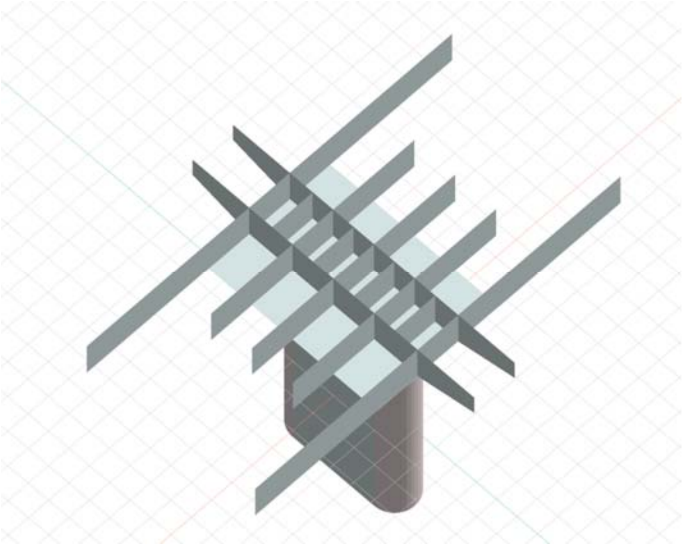
This chapter will demonstrate that stresses from global analyses based on full general cross sections, gives results to safe side.

To estimate the effect of shear-lag, a simplified FEM-model using the program FEM-Design has been established. 360 meter of the girder is modelled with symmetry boundary conditions at each end of the model as shown below. The stiffened plates are modelled as unstiffened plates with equivalent plate thicknesses. The modelled cross-section do not represent the exact chosen cross-section, but is considered to be sufficient for this study.



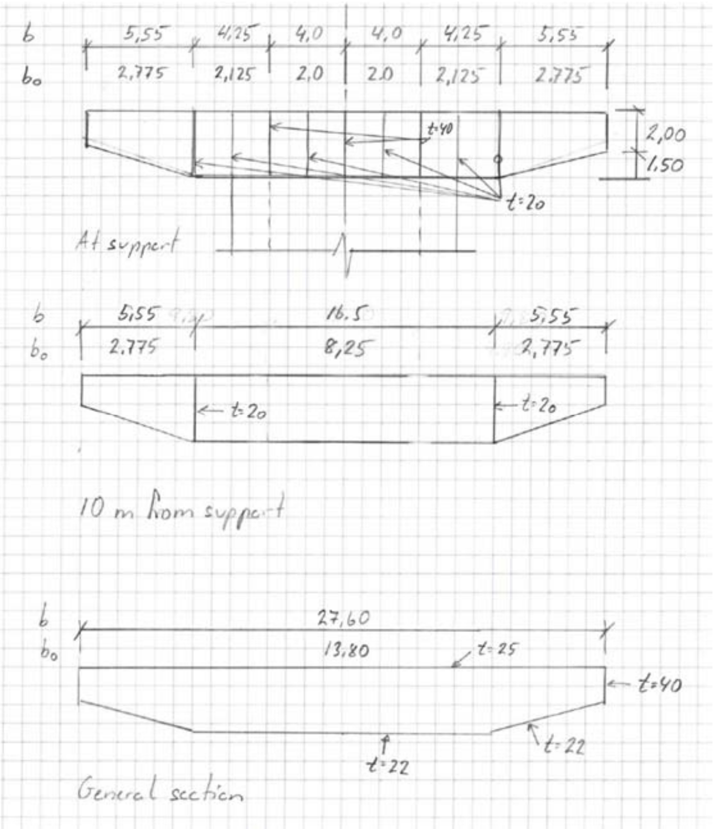
Shell-model from FEM-Design

The reinforcement at the connection between girder and column is shown below. 2 transverse bulkheads align with the columns long side. 9 longitudinal bulkheads are arranged mainly based on ship impact studies reported in chapter 6.



Reinforcement at column-girder connection

The following cross sections are used in the study:



All plates are modelled with equivalent plate thickness:

• Deck plate	25 mm
• Vertical side plate	40 mm
• Bottom plates	22 mm
• Longitudinal bulkheads	20 and 40 mm

The arrangement of longitudinal bulkheads has been developed through several iterations. The outermost bulkheads are longer than the others, and this elongation have a positive effect with respect to shear-lag. Studies shows that additional elongations do not have significantly better effect.

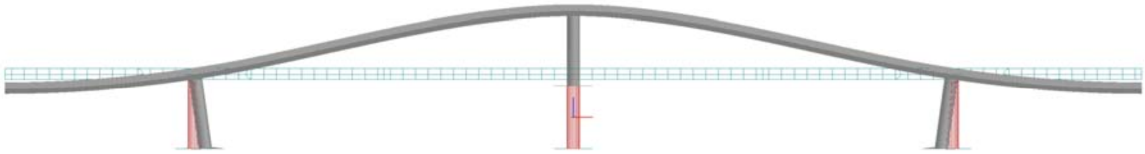
	$I\ m^4$	$W_{ok}\ m^3$	$W_{uk}\ m^3$
At support - reduced for shear lag	5,449	3,597	2,745
10 m from support - reduced for shear lag	3,659	2,299	1,917
At midspan - reduced for shear lag	3,097	2,017	1,577
At midspan - no reduction	3,519	2,422	1,719

The table shows the section properties. Reduction due to shear lag is calculated according to NS-EN 1991-1-5 section 3.2.

Two load cases are studied for the shear-lag effect.

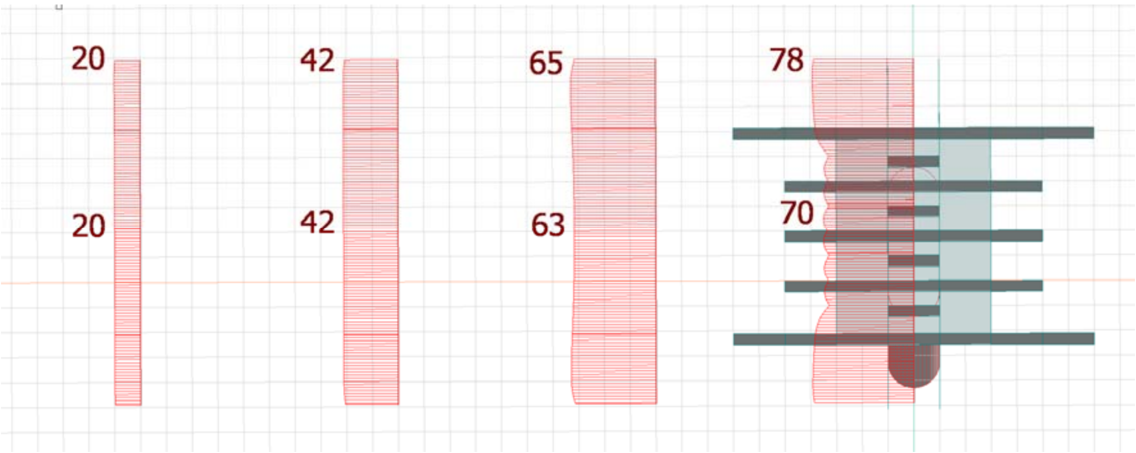
Forced displacement:

The middle column is given a forced displacement 1 meter upwards. This is considered to represent a typical deformed shape of the girder.



Forced displacement for study of shear-lag effect

Results are presented below. This shows stress distribution over the deck-width at the column and at 20, 40 and 60 meters from the column. We see that there is some shear-lag effect at the column, but no effect in the span.



Stress-distribution in bridge-deck

The forced displacement will, assuming constant stiffness along the girder, give linear varying bending moment along the girder. The stress distribution along the girder will therefor also vary linear. From the figure above, we could therefor expect stresses 20 MPa – 42 MPa – 64 MPa and 86 MPa at the 4 sections without shear-lag effect, since the stress increases with 22 MPa in each 20-meter step when shear-lag effect is disregarded.

We see that stresses at section 1,2 and 3 fulfills this assumption. Stresses at section 4 – support – is lower (90%) than expected (78 against 86). The reinforcement at the column increases the capacity and compensates the reduction due to shear-lag. The increased capacity also compensates that increased stiffness attracts more bending in a forced displacement load situation.

Increased capacity should reduce the stress to 0,67. When the reduction is only to 0,9, it means that increased stiffness increases the bending moment with 0,9/0,67 = 1,34

Distributed permanent load:

The shear lag effect is studied for an equally distributed load situation.
A load intensity p = 179 kN/m is applied.

Figure shows displacement from permanent load

Hand calculations gives the following bending moments:

$M(x) = 179*120^2/2*(x/120 - x^2/120^2 - 1/6)$ where x = 0 is at support and 120 is span

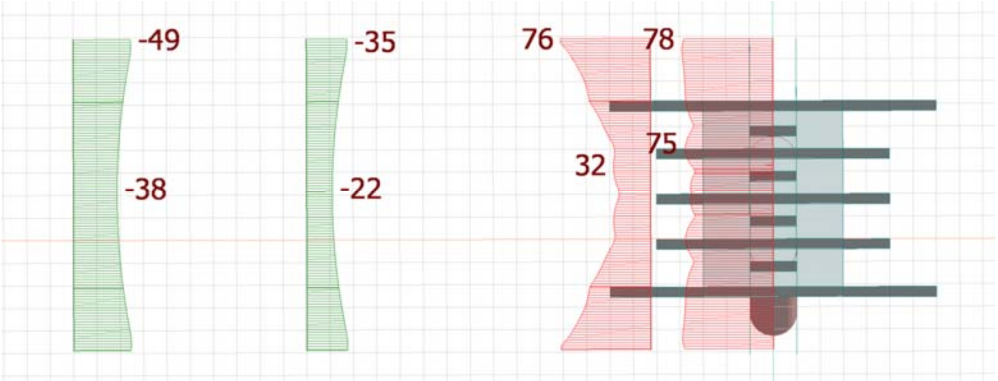
M(0) = -215 MNm
M(10.5) = -112 MNm
M(60) = 107 MNm

Stresses are calculated with reinforced cross section included shear lag effects and with the general cross section without reduction for shear lag. Results are given below:

		With Shear lag effects	General cross section
	M	s_{ok}	s_{ok}
x = 0	-215	-60	-89
x = 10.5	-112	-49	-46
x = 60	107	53	44

We see that stresses at support, calculated with the general section gives stresses 50% higher than actual stresses. 10,5 m from support, the stresses are about the same. At mid span, actual stresses are 20% higher due to shear lag effect.

We now look at the results from the FEM-analyses, shown below:



Stress-distribution in bridge-deck

We observe that there is almost no shear lag at support, but the stresses are 30% higher than hand calculations – 78 MPa against 60 MPa. Compared to stresses from general cross section, the stresses are 88% (78 against 89)

At mid span, we observe shear lag effect, but the stresses are some lower than hand calculations – 49 MPa against 53 MPa.

It is reasonable to conclude that these differences are a result of increased stiffness at supports. Higher stiffness will result in some higher bending moments. Increased capacity should reduce the stress to 0,67. When the reduction is only to 0,88, it means that increased stiffness increases the bending moment with 0,88/0,67 = 1,31

It also shows that the shear lag is significant 10 m from support, with stresses 50 – 60 % higher than expected. The stress is, however, not higher than at support and still 15% lower than the stress at support calculated from the general cross section.

Stresses in bottom plates from the analyses is also compared with hand calculations in a similar way. The results are summarized in the table below. Using stresses from general cross sections without share lag effect, overestimates stresses with 25% at support.

Conclusions

To summary the results, results from FEM-analyses and hand calculations based on general cross sections are presented in table below:

Deck	Forced displacement		Permanent load	
	FEM Analyses	Hand calc	FEM Analyses	Hand calc
x = 0	78	86	78	89
x = 10.5	-	-	76	46
x = 60	20	20	49	44

Bottom	Forced displacement		Permanent load	
	FEM Analyses	Hand calc	FEM Analyses	Hand calc
x = 0	98	117	100	125
x = 10.5	-	-	80	65
x = 60	27	27	59	62

Calculating stresses from global analyses based on general cross sections without reinforcements at supports, and without considering reduction due to share lag, have the following consequences:

- At support deck stresses are overestimated with typically 10 %. Results are conservative
- At support bottom stresses are overestimated with typically 25 %. Results are conservative
- At midspan deck stresses are underestimated with typically 0 - 10%.
- This is not significant for fatigue since load case forced displacement is considered to represent dynamic loads better.
- This is not critical for ULS since the stress level in span is generally lower than at supports.
- At midspan bottom stresses is equal
- 10 meters from support stresses are underestimated, but stresses are lower than at support. Stress check at support is sufficient.

Calculating girder stresses based on cross section in global analyses without considering shear lag effects or increased stiffness du to reinforcements, gives valid results for FLS and ULS checks.