Appendix to report:

SBJ-33-C5-OON-22-RE-016

FATIGUE ASSESSMENT

Appendix title:

Appendix B - Local traffic fatigue methodology

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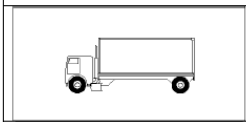
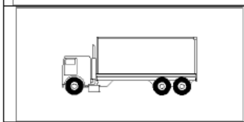
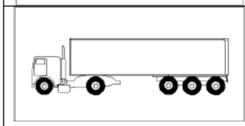
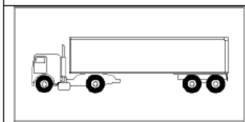
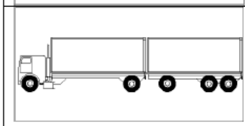
CONCEPT DEVELOPMENT FLOATING BRIDGE E39 BJØRNAFJORDEN

Table of Content

1 GENERAL

Fatigue damage for the stiffeners of the orthotropic bridge deck from local traffic actions is considered in this section. Fatigue load model 4 from NS-EN 1991-2 as shown in the figure below is used as the fatigue load.

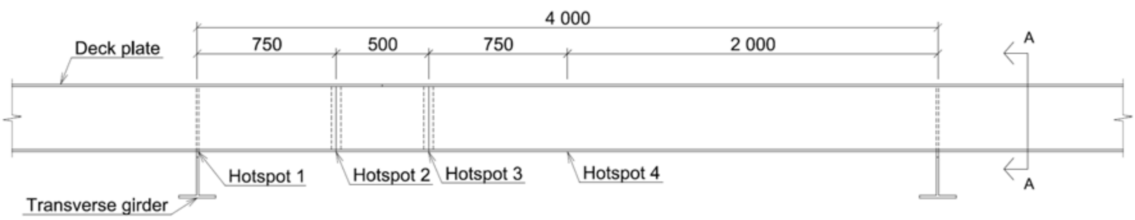
Table 4.7 - Set of equivalent lorries

VEHICLE TYPE			TRAFFIC TYPE			
1	2	3	4	5	6	7
			Long distance	Medium distance	Local traffic	
LORRY	Axle spacing (m)	Equivalent axle loads (kN)	Lorry percentage	Lorry percentage	Lorry percentage	Wheel type
	4,5	70 130	20,0	40,0	80,0	A B
	4,20 1,30	70 120 120	5,0	10,0	5,0	A B B
	3,20 5,20 1,30 1,30	70 150 90 90 90	50,0	30,0	5,0	A B C C C
	3,40 6,00 1,80	70 140 90 90	15,0	15,0	5,0	A B B B
	4,80 3,60 4,40 1,30	70 130 90 80 80	10,0	5,0	5,0	A B C C C

> *Figure 1: Equivalent lorries used in fatigue design; fatigue load model 4*

The stiffeners are considered as continues beams supported by the transverse girders with span widths of 4,0 m. The critical hotspots for fatigue in the stiffeners are:

- Hotspot 1: At the supports where the transverse girders are welded to the stiffeners (Point 1, x = 12,0 m in figures below)
- Hotspot 2: At the splicing of the stiffeners 0.75 m from the supports (Point 2, x = 12,75 m in figures below)
- Hotspot 3: At the splicing of the stiffeners 1,25 m from the supports (Point 3, x = 13,25 m in figures below)
- Hotspot 4: At midspan of stiffeners 2,00 m from the supports (Point 4, x = 14,0 m in figures below)



> *Figure 2: Sketch of hotspots considered*

The calculation of stress ranges is done with a continues beam model with point loads. A shell element model is used to adjust the stress ranges since the wheel pressures are surface loads and that there is some load shedding between neighbouring stiffeners.
Some simplifications are made:

- All the lorries are assumed to be centred in the notional lane and the notional lane is assumed to be positioned so that the centre of the wheels will be centred over one stiffener. NS-EN 1991-2 section 4.6.1(5) states that for orthotropic bridge decks a statistical distribution of the transverse position should be considered according to the below figure.

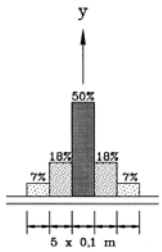


Figure 4.6 - Frequency distribution of transverse location of centre line of vehicle

> *Figure 3: Distribution of vehicle centre line in a lane*

- The wheel pressure loads are considered as point loads in the beam model. A shell element model is used to adjust the stress levels for the distribution of the wheel pressure over the contact surface of the bridge deck and the distribution of loads between neighbouring stiffeners (see chapter 2.4).

These simplifications lead to a conservative estimate of the stress ranges.

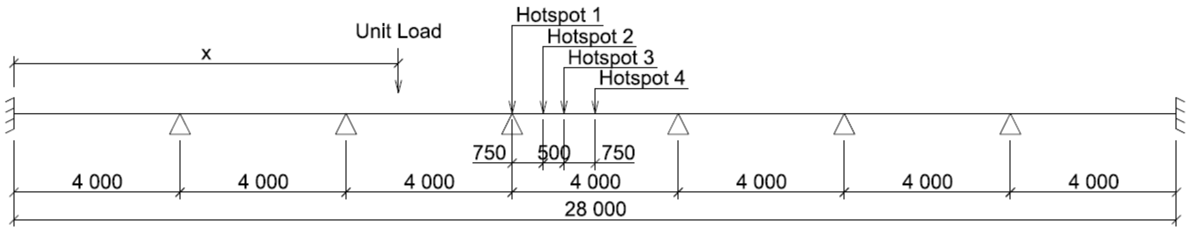
1.1 Detail classification and fatigue S-N curves

S-N curves for structures in air from DNV-RP-C203 is used for the fatigue design. The choice of S-N curves for each of the four hotspots is explained below.
Hotspot 1: At this hotspot the transverse girders are welded with fillet welds to the webs of the stiffeners. The thickness of the plates of the transverse girder is 12 mm and fatigue curve E is chosen for this detail.
Hotspot 2 and 3: At these hotspots the stiffeners are welded with a transverse butt weld from one side with a backing strip. NS-EN 1993-1-9 table 8.8 for closed stringers categorizes this detail as fat. class 71 which corresponds to fat. curve F in DNV-RP-C203. It is therefore chosen to use fatigue curve F for these details. Acc. to NS-EN it has not been used any SCF as this is included in the detail category within normal tolerances.
Hotspot 4: At this detail it is assumed no welding and fatigue curve C is chosen (base material).

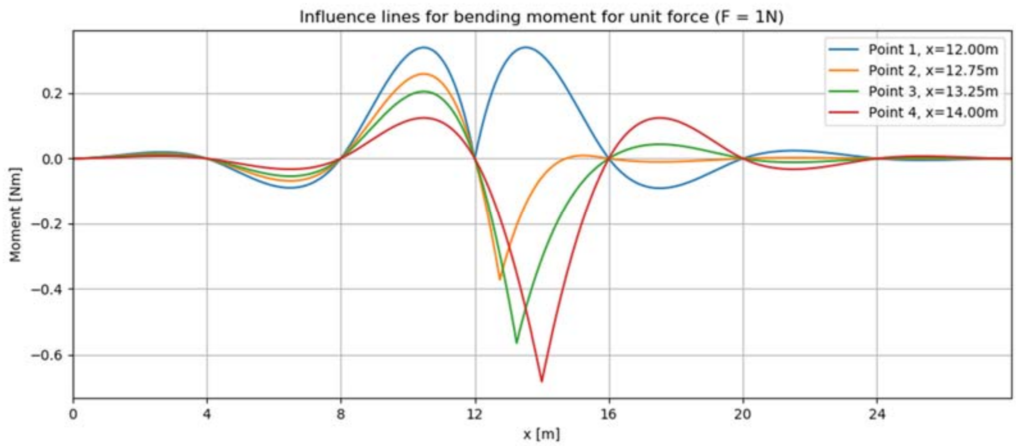
2 CALCULATIONS

2.1 Beam model and calculation of influence lines

As mentioned, the stiffeners are considered as continues beams supported by the transverse girders. Therefore, a simple beam model is used to construct the influence lines for bending moment for the four hotspots where fatigue damage is calculated. The static model used is a continues beam over seven spans and is shown in the figure below.

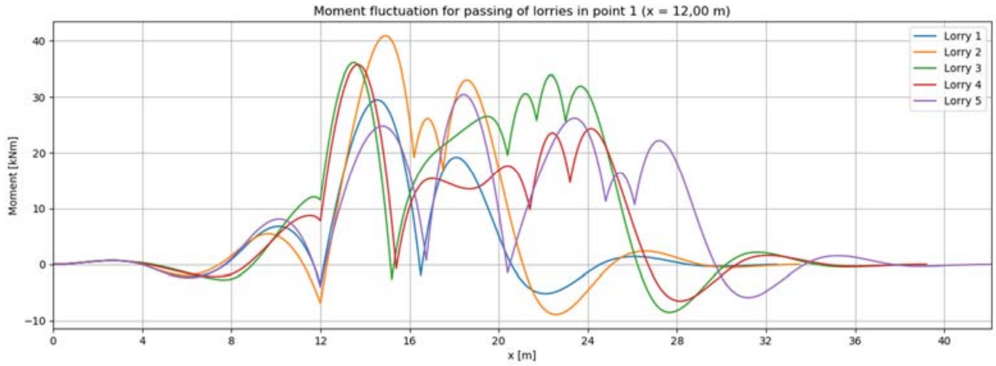


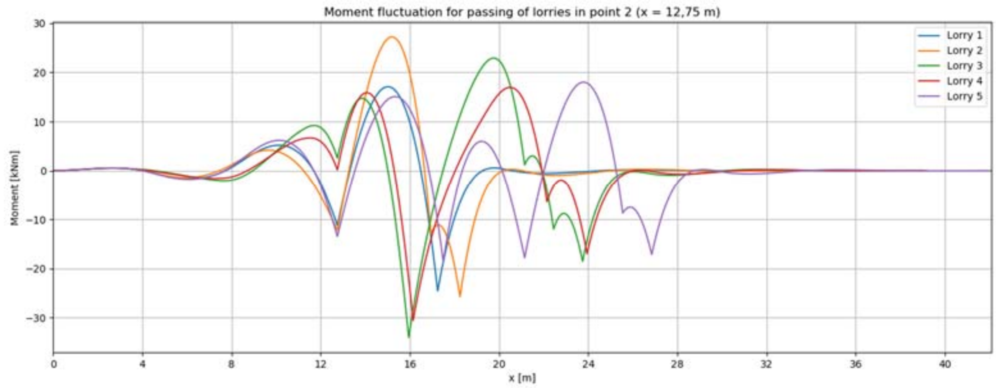
This static model is used to construct the influence lines for bending moment in the hotspots shown in the figure for a unit load passing over the beam. The calculated influence lines are shown in the figure below.

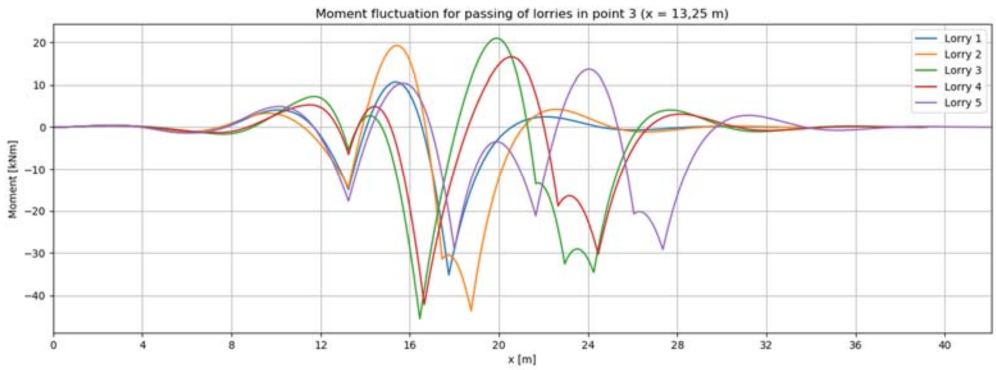


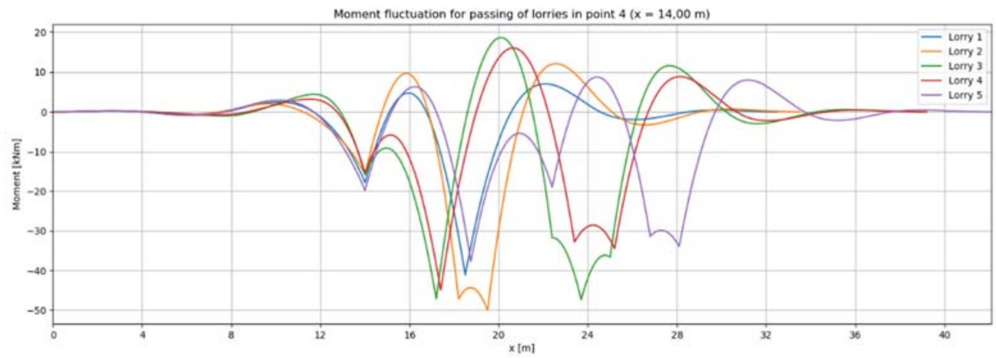
2.2 Moment fluctuations in the stiffeners for passing lorries

For all the five lorries the moment fluctuation in the stiffeners at hotspot 1 to 4 are calculated for the lorry passing over the beam model. The influence lines are used for these calculations. The axle loads shown in the table on the first page consists of to wheel pressure loads. The point loads used to calculate the moments is therefore half the axle loads.
The moment fluctuations in hotspot 1 to 4 for each type of lorry is shown in the figures below.


Moment fluctuation for passing of lorries in point 1 (x = 12,00 m)
Moment [kNm]
x [m]
Lorry 1
Lorry 2
Lorry 3
Lorry 4
Lorry 5

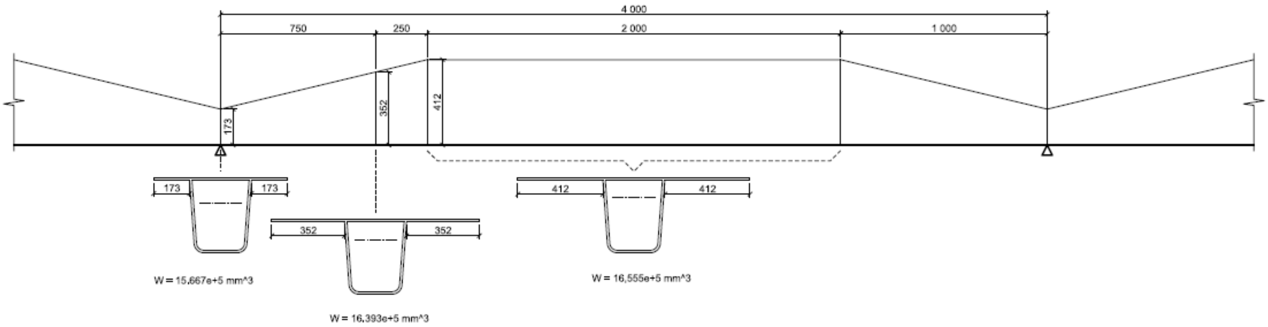

Moment fluctuation for passing of lorries in point 2 (x = 12,75 m)
Moment [kNm]
x [m]
Lorry 1
Lorry 2
Lorry 3
Lorry 4
Lorry 5


Moment fluctuation for passing of lorries in point 3 (x = 13,25 m)
Moment [kNm]
x [m]
Lorry 1
Lorry 2
Lorry 3
Lorry 4
Lorry 5


Moment fluctuation for passing of lorries in point 4 (x = 14,00 m)
Moment [kNm]
x [m]
Lorry 1
Lorry 2
Lorry 3
Lorry 4
Lorry 5

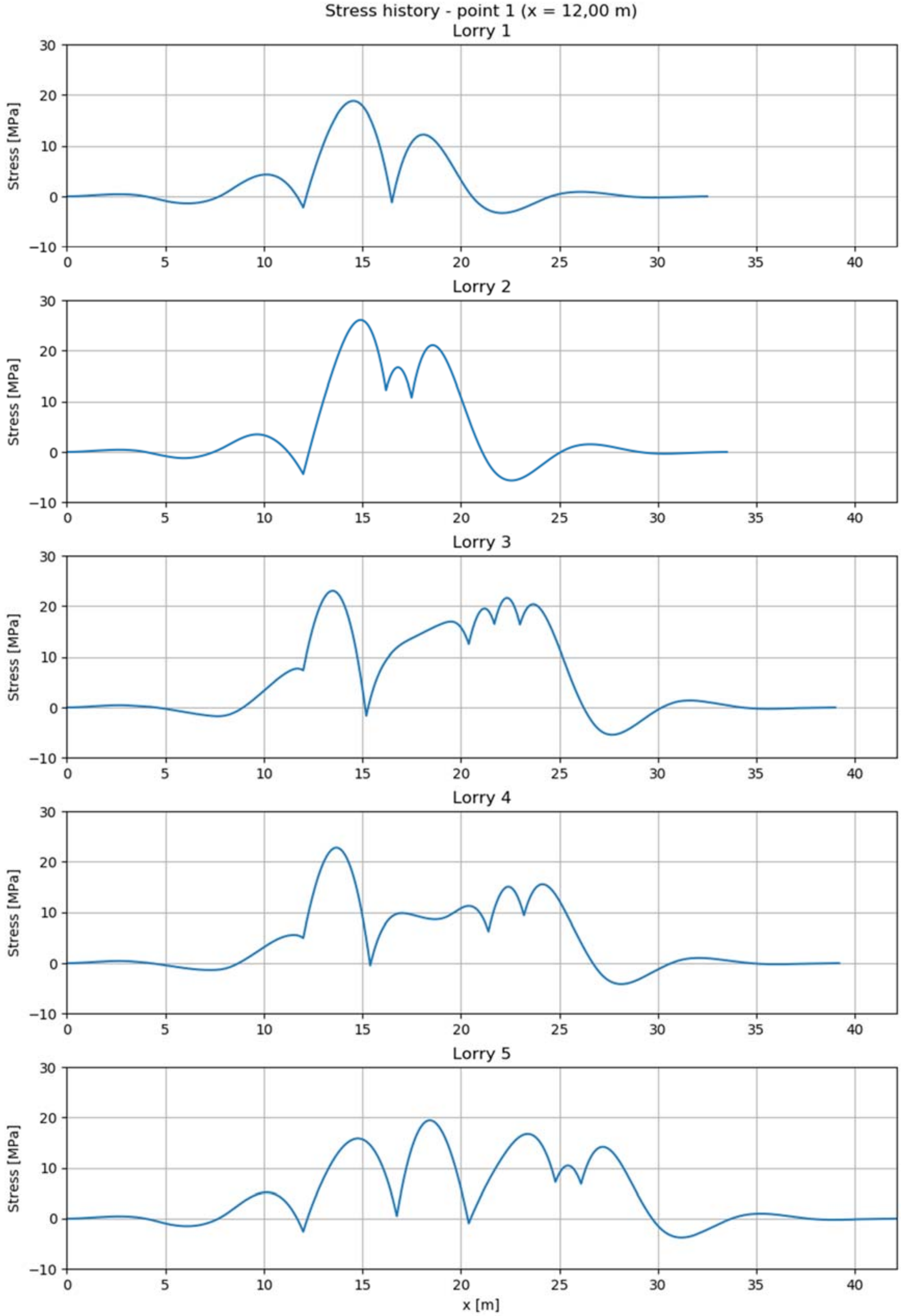
2.3 Stress history in the stiffeners due to passing lorries

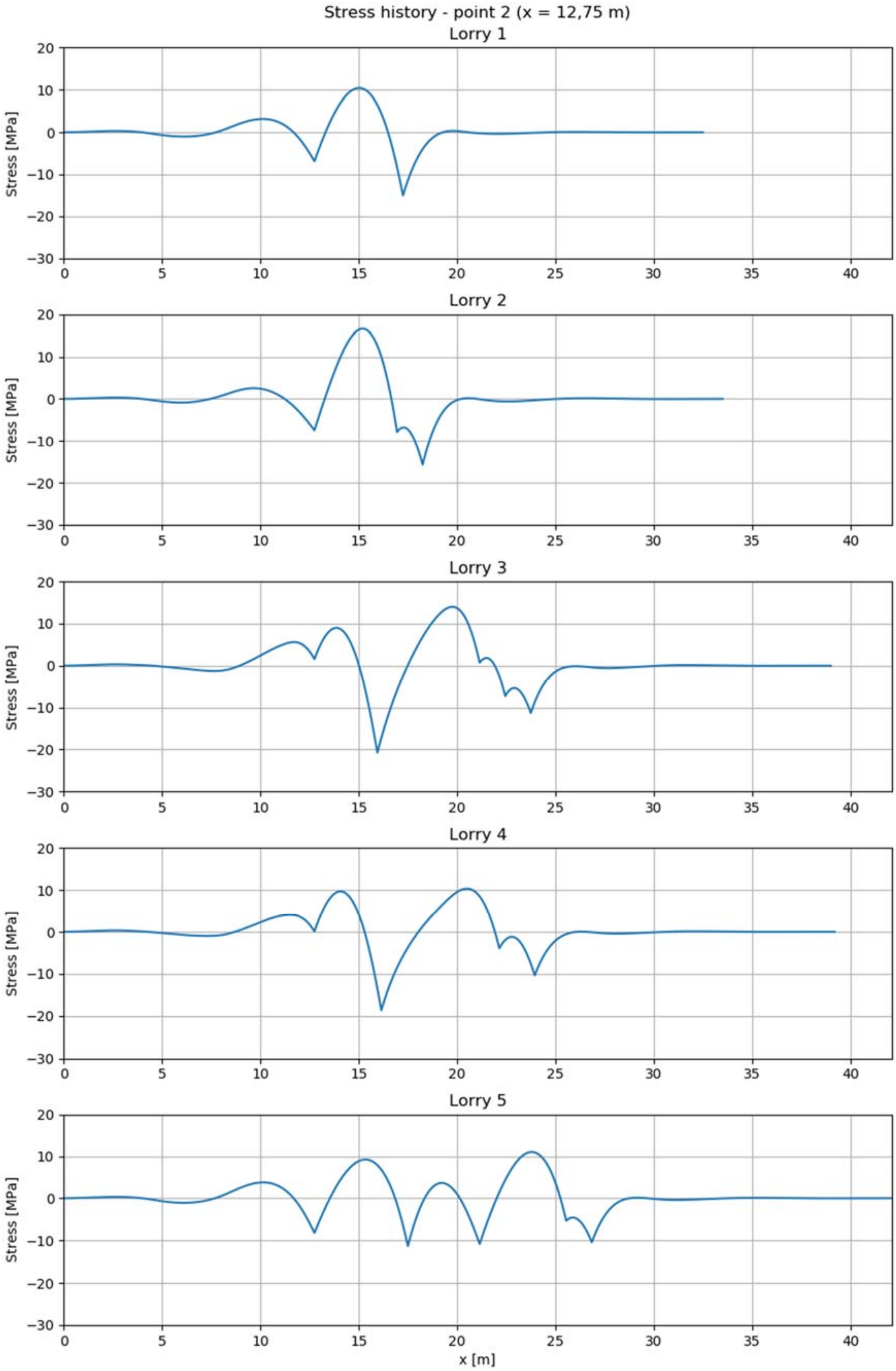
A stress history is calculated for a general stiffener profile.
The nominal stress history is calculated for a general stiffener from the moment fluctuations in the figures above. The cross-section modulus used to calculate the stresses is shown for the different points in the figure below. The effective part of the deck plate is smaller at the supports than in the span of the stiffeners.

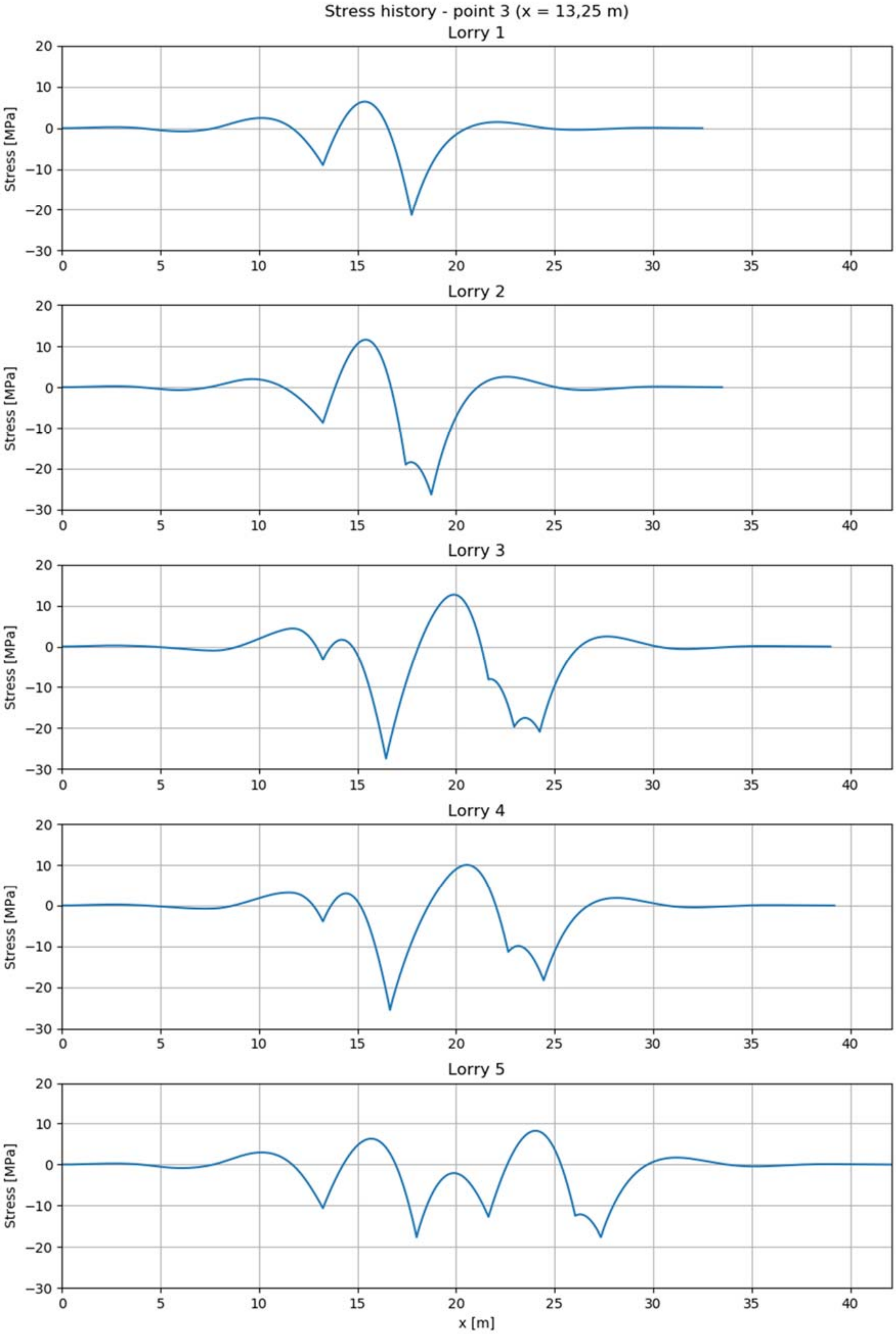


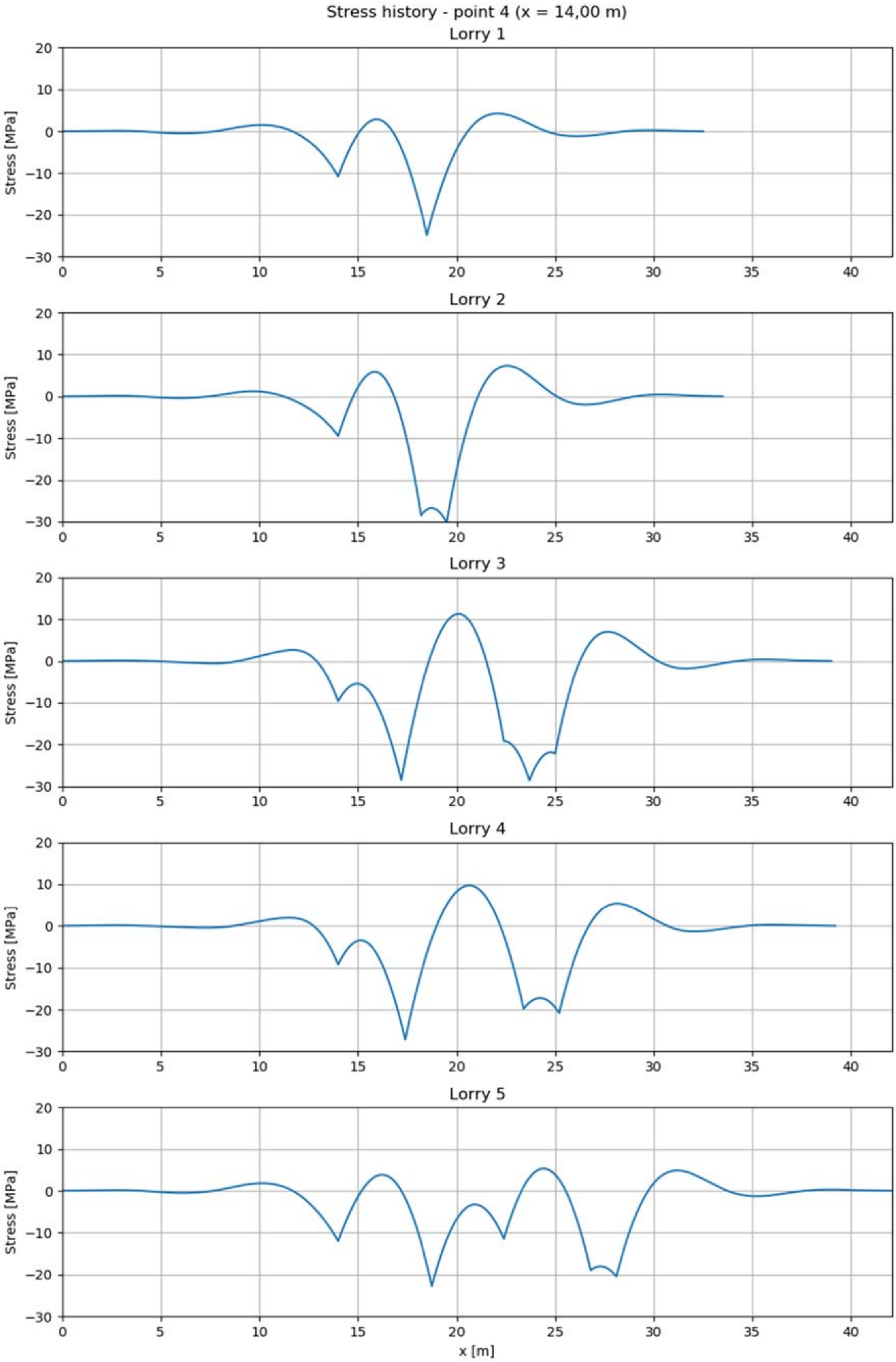
> *Figure 4: Effective cross-section, general stiffener profile.*

This general profile is used as basis for stiffener design and stress range calculations.
Stress histories for the five different lorries in each of the four points is shown in the figures below.


Stress history - point 1 (x = 12,00 m)
Lorry 1
Lorry 2
Lorry 3
Lorry 4
Lorry 5
Stress [MPa]
x [m]
30
20
10
0
−10
0
5
10
15
20
25
30
35
40

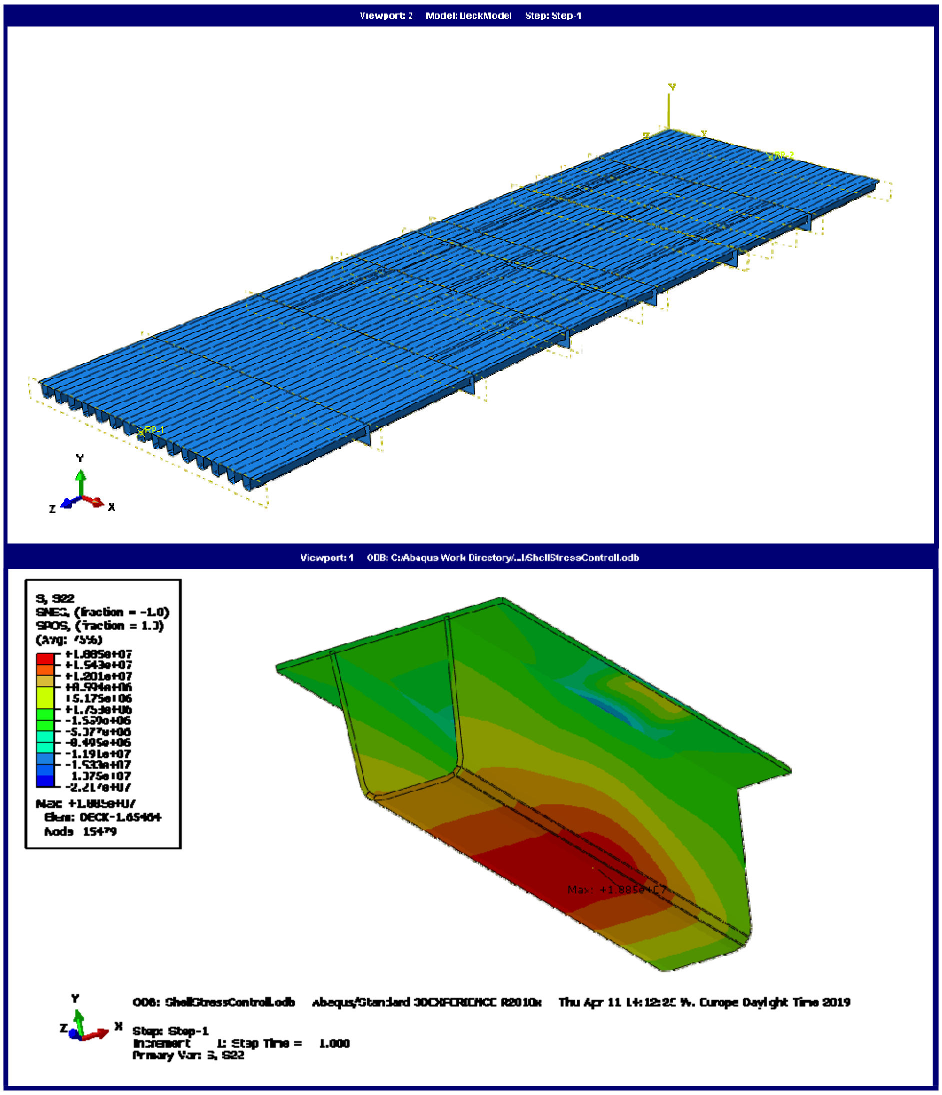

Stress history - point 2 (x = 12,75 m)
Lorry 1
Lorry 2
Lorry 3
Lorry 4
Lorry 5
Stress [MPa]
x [m]


Stress history - point 3 (x = 13,25 m)
Lorry 1
Lorry 2
Lorry 3
Lorry 4
Lorry 5
Stress [MPa]
x [m]
20
10
0
−10
−20
−30
0
5
10
15
20
25
30
35
40


Stress history - point 4 (x = 14,00 m)
Lorry 1
Lorry 2
Lorry 3
Lorry 4
Lorry 5
Stress [MPa]
x [m]

2.4 Comparison of stress levels from the beam analysis with shell element analysis

It is seen that Hotspot 3 is the critical hotspot for fatigue damage in the orthotropic bridge deck. This hotspot is therefore further investigated with a shell element model. It is seen from the stress plots above that the largest stress level in the bottom of stiffener comes from lorry 3. When the centre of the front axle is in position x = 16,45 m (which corresponds to the centre of axle 2 centric over the hotspot) the largest stress is found. The stress level is then 27,472 MPa.
A shell element analysis of the whole bridge deck with an identical load position is performed to calculate the ratio between beam model stresses and shell model stresses. The loads are modelled as surface loads with an extension equal to the contact surfaces given in NS-EN 1991-2 table 4.8 plus 80 mm in each direction due to distribution through the asphalt. The maximum stress in the stiffener in the hotspot is found to be 18,85 MPa as shown in the figure below.



> *Figure 5: Stress distribution shell model*

The stress levels from the beam model is therefore corrected with a factor equal to:
α = 18,85 / 27,472 = 0,69

2.5 Stress ranges, cycle counting and design life

The rain-flow counting method is adopted to calculate the stress ranges and numbers of cycles for each stress range for all five types of lorries in each of the four points. Rain-flow counting is performed on the stress history diagrams calculated with the beam model. The stress ranges are then corrected with the factor α calculated in the previous section.
The total number of lorries passing the bridge in each slow lane is assumed to be $0{,}5*10^6$ lorries pr. year. Long distance traffic type is assumed and the statistical distribution of types of lorries is collected from table 4.7 in NS-EN 1991-2.
The yearly damage is calculated by the Palmgren-Miner rule:

$$D_{year} = \sum_{i=1}^{k} \frac{n_i}{N_i}$$

Where n_i is the number of cycles of a stress range and N_i is the number of cycles to failure at the same stress range. N_i is calculated based on the S-N curves:
$$N_i = 10^{\log a - m \, log \Delta\sigma_i}$$
The design life of the hotspot is then calculated by the formula:

$$\text{Design life} = \frac{1}{D_{year} * DFF}$$

Where DFF is the design fatigue factor 2,5 is used for the stiffeners.
These calculations are shown for the critical detail, hotspot 3, in the table below. The design life for hotspot 3 for the general stiffener shown due to local traffic only is calculated to be 104 years. When combined with environmental loads, the fatigue life will not be sufficient, hence a welded box stiffener is used directly under wheelbases in the slow lanes. Stress ranges are scaled accordingly with a factor based on the section modulus of the welded profile, ref. chapter 3.1.

> *Table 1: Results from local traffic fatigue calculations for a general stiffener profile.*

Hotspot 3	At joints in stiffeners				
Detail:	Butt weld of stiffeners				
S-N curve:	F				
log a2	15,091	m2	5	Fat lim	41,52
DFF	2,5				
NOBS	500000	Total yearly number of lorries in each slow lane			
Stress factor α	0,69	Stress distribution factor from FEM analysis			
Lorry 1	20 %	of NOBS gives	100000	Lorries of this type pr. year	
Stress range	Adjusted stress range	Cycles pr. lorry	Cycles pr. year	N cycles to fail	Yearly damage
0,252012	0,174	0,5	50000	7,756E+18	6,446E-15
1,04116	0,718	0,5	50000	6,444E+15	7,759E-12
3,26819	2,255	0,5	50000	2,115E+13	2,365E-09
11,501	7,936	0,5	50000	3,918E+10	1,276E-06
15,5047	10,698	0,5	50000	8,799E+09	5,682E-06
27,7512	19,148	0,5	50000	4,790E+08	1,044E-04
22,757	15,702	0,5	50000	1,292E+09	3,871E-05
1,8967	1,309	0,5	50000	3,212E+14	1,557E-10
0,507524	0,350	0,5	50000	2,341E+17	2,135E-13
0,0993987	0,069	0,5	50000	8,126E+20	6,153E-17
MAX STRESS RANGE	19,148			SUM Lorry 1	1,500E-04
Lorry 2	5 %	of NOBS gives	25000	Lorries of this type pr. year	
Stress range	Adjusted stress range	Cycles pr. lorry	Cycles pr. year	N cycles to fail	Yearly damage
0,252012	0,174	0,5	12500	7,756E+18	1,612E-15
0,951944	0,657	0,5	12500	1,009E+16	1,239E-12
2,69586	1,860	0,5	12500	5,537E+13	2,258E-10
10,6987	7,382	0,5	12500	5,625E+10	2,222E-07
20,3215	14,022	0,5	12500	2,275E+09	5,495E-06
0,593179	0,409	1	25000	1,074E+17	2,329E-13
37,9425	26,180	0,5	12500	1,003E+08	1,247E-04
28,8835	19,930	0,5	12500	3,922E+08	3,187E-05
3,2505	2,243	0,5	12500	2,173E+13	5,753E-10
0,84366	0,582	0,5	12500	1,845E+16	6,776E-13
0,152842	0,105	0,5	12500	9,452E+19	1,322E-16
MAX STRESS RANGE	26,180			SUM Lorry 2	1,623E-04
Lorry 3	50 %	of NOBS gives	250000	Lorries of this type pr. year	
Stress range	Adjusted stress range	Cycles pr. lorry	Cycles pr. year	N cycles to fail	Yearly damage
0,252012	0,174	0,5	125000	7,756E+18	1,612E-14
1,24654	0,860	0,5	125000	2,620E+15	4,772E-11
5,39999	3,726	0,5	125000	1,717E+12	7,280E-08
4,91748	3,393	1	250000	2,742E+12	9,118E-08
31,8774	21,995	0,5	125000	2,395E+08	5,219E-04
0,0987871	0,068	1	250000	8,380E+20	2,983E-16
2,14927	1,483	1	250000	1,719E+14	1,454E-09
40,1413	27,697	0,5	125000	7,565E+07	1,652E-03
33,586	23,174	0,5	125000	1,845E+08	6,776E-04
23,3707	16,126	0,5	125000	1,131E+09	1,105E-04
3,08159	2,126	0,5	125000	2,837E+13	4,406E-09
0,753611	0,520	0,5	125000	3,244E+16	3,854E-12
0,12611	0,087	0,5	125000	2,472E+20	5,057E-16
MAX STRESS RANGE	27,697			SUM Lorry 3	2,963E-03
Lorry 4	15 %	of NOBS gives	75000	Lorries of this type pr. year	
Stress range	Adjusted stress range	Cycles pr. lorry	Cycles pr. year	N cycles to fail	Yearly damage
0,252012	0,174	0,5	37500	7,756E+18	4,835E-15
1,02474	0,707	0,5	37500	6,977E+15	5,375E-12
3,96035	2,733	0,5	37500	8,093E+12	4,634E-09
6,86052	4,734	1	75000	5,188E+11	1,446E-07
28,6186	19,747	0,5	37500	4,107E+08	9,131E-05
1,4499	1,000	1	75000	1,230E+15	6,095E-11
35,4366	24,451	0,5	37500	1,411E+08	2,658E-04
28,3107	19,534	0,5	37500	4,335E+08	8,650E-05
20,179	13,924	0,5	37500	2,356E+09	1,591E-05
2,3445	1,618	0,5	37500	1,113E+14	3,369E-10
0,567073	0,391	0,5	37500	1,344E+17	2,789E-13
0,0964526	0,067	0,5	37500	9,445E+20	3,971E-17
MAX STRESS RANGE	24,451			SUM Lorry 4	4,597E-04
Lorry 5	10 %	of NOBS gives	50000	Lorries of this type pr. year	
Stress range	Adjusted stress range	Cycles pr. lorry	Cycles pr. year	N cycles to fail	Yearly damage
0,252012	0,174	0,5	25000	7,756E+18	3,223E-15
1,10605	0,763	0,5	25000	4,763E+15	5,249E-12
3,80829	2,628	0,5	25000	9,842E+12	2,540E-09
13,6144	9,394	0,5	25000	1,686E+10	1,483E-06
16,975	11,713	0,5	25000	5,594E+09	4,469E-06
10,6823	7,371	1	50000	5,668E+10	8,821E-07
23,9509	16,526	0,5	25000	1,000E+09	2,499E-05
0,342127	0,236	1	50000	1,682E+18	2,973E-14
25,8825	17,859	0,5	25000	6,788E+08	3,683E-05
25,8661	17,848	0,5	25000	6,809E+08	3,671E-05
19,3144	13,327	0,5	25000	2,933E+09	8,523E-06
2,14488	1,480	0,5	25000	1,737E+14	1,439E-10
0,552052	0,381	0,5	25000	1,538E+17	1,626E-13
0,101895	0,070	0,5	25000	7,178E+20	3,483E-17
MAX STRESS RANGE	17,859			SUM Lorry 5	1,139E-04
			Sum yearly damage all lorries		0,00384842
			Fatigue life (years), incl DFF		103,94

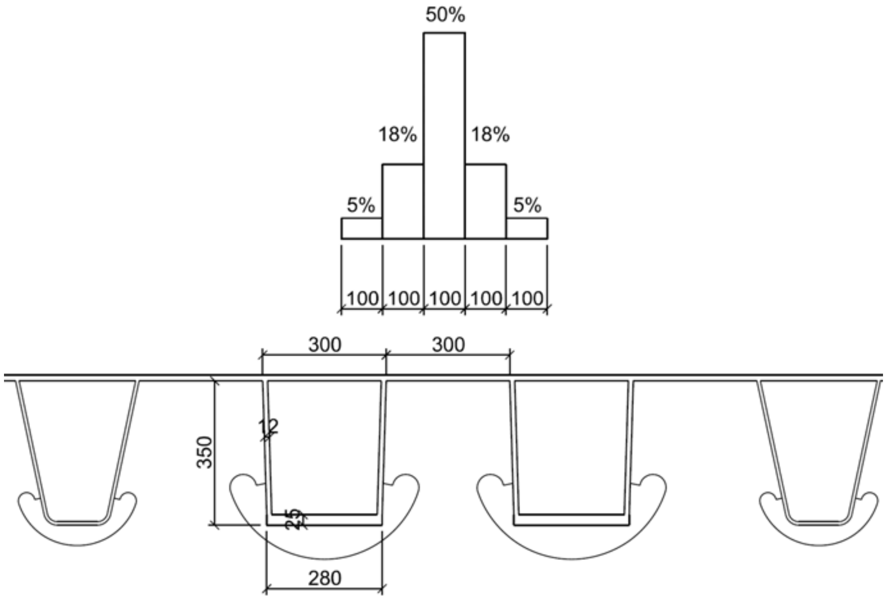
3 DISCUSSION

This method of calculating stress ranges is considered to be a conservative estimate based on the following points:

- The load will spread out to other stiffeners hence reduce the stress range for the considered hot-spot, when the lorry is farther away from the considered hot-spot. This effect has not been considered in detail here but should be studied further at a later stage.
- The stress reduction factor (from beam to FE model) is calculated when the largest wheel pressure is directly above the hotspot. For any other position of the loads the distribution of loads to neighbouring stiffeners will be larger and this factor will be smaller. The factor is therefore conservatively used for all load positions.
- The effect of varying stiffness in mid span and at columns for calculation of local fatigue damage has not been accounted for. This effect is studied further in the next section regarding combination of local traffic stresses with stresses from global loads. It is found to have some effect in mid span, but less over columns.
- It has been assumed that all traffic is running in the centre of the slow lane and affecting the same stiffener, but the traffic will generally spread out to a greater extent. This has not been accounted for at this stage. This is due to the large wheel width of axle B of lorry 3, which is the lorry giving the largest stress range (and accounting for 50 % of all lorries). Moving some traffic off the centre line per Figure 3, will still result in stiffeners being subjected to direct loading.

3.1 Improved trapezoidal stiffener

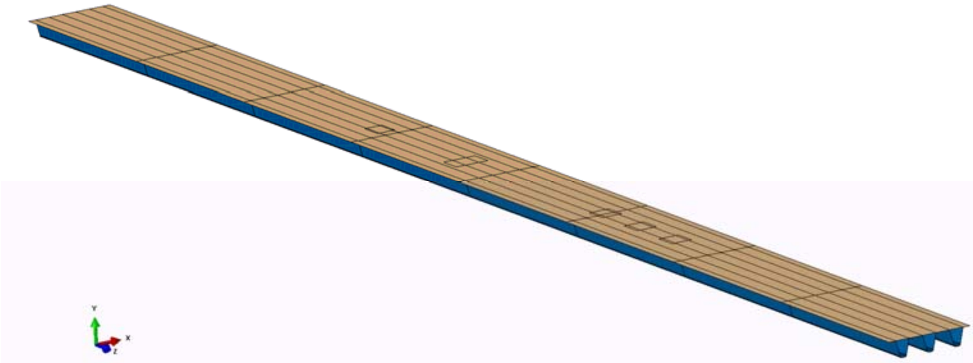
A fatigue life of 104 years from local traffic alone was calculated for the general stiffener profile in section 2.5This led to insufficient fatigue life in combination with other loads. To achieve approx. 100 years fatigue life using the comb. formula, the stresses were scaled with a factor based on the section modulus of a reinforced stiffener geometry. It was seen that it was needed to scale the stresses with a factor of about 0,4, which led to a section modulus of about 2,5 times that of the general stiffener profile. In addition, stiffeners are placed such that the centre line of the wheels hit directly between two stiffeners as shown on the figure below. This led to a significant reduction of stresses (as shown in chapter 3.3).



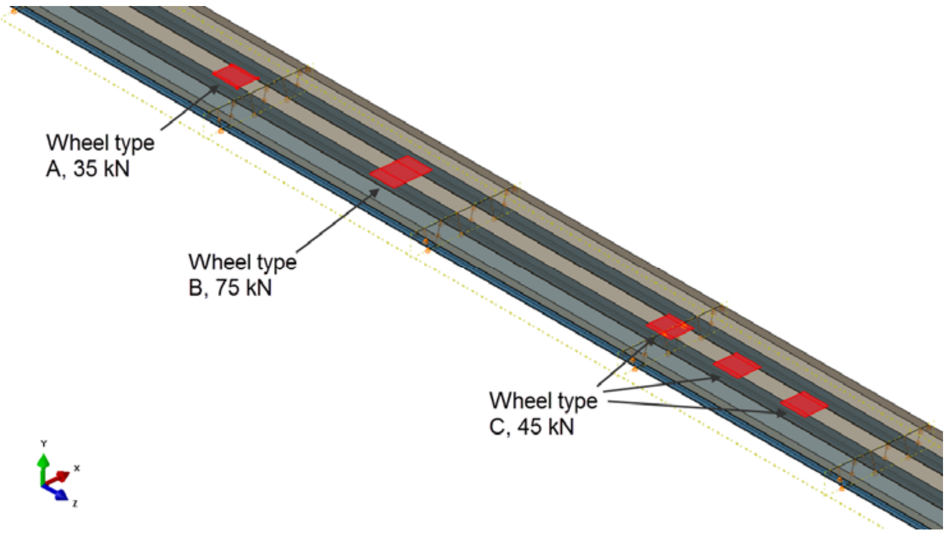
> *Figure 6: Improved stiffener and distribution of traffic.*

3.2 Study of effect of varying stiffness along the girder

Global traffic actions on the bridge girder is analysed with a beam model. Hence, global traffic loads will give compressive stresses in the upper flange of the girder (including the stiffeners connected to the top plate) when a vehicle is positioned in the mid span between two columns.
The stresses that are calculated in the stiffeners in the previous section does not account for these compressive stresses that will result in reduced tensile stresses locally in the stiffener. To account for and evaluate this effect, two shell models have been created. One model of three stiffeners that is simply supported at each transverse girder which spans over 32 m, see figures below (model A, for local effects). Wheel pressures from one set of wheels from lorry 3 has been applied at 5 points in accordance with [1].

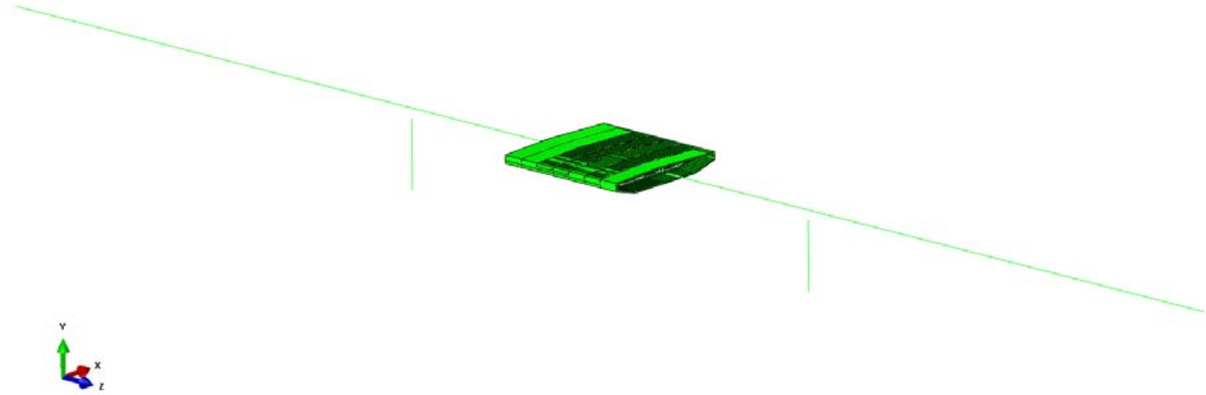


> *Figure 7: Local shell model of stiffeners. Model A*

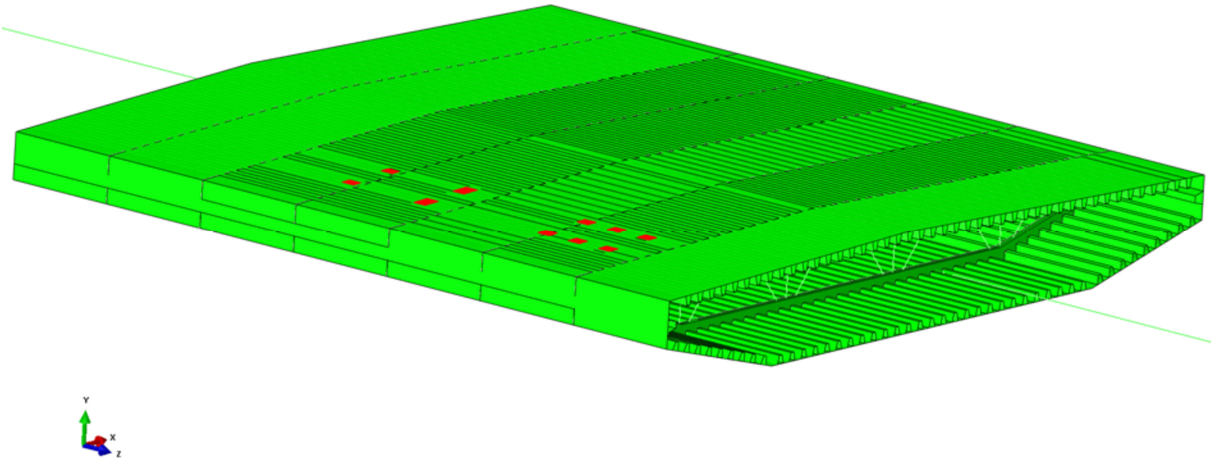


> *Figure 8: Loads from one set of wheels (half of axle load). Model A*

The second model, B, is a combined beam and shell model of a part of the bridge girder that is rigidly connected to beam elements and, in turn, columns (model B, for study of global effects). Element size of approximately 50 mm. The same wheel pressure as the first model from lorry 3 has been applied (except for two sets of wheels). The stresses found in this model will include the compressive stresses due to the global boundary conditions which yields compression in the upper stiffeners. These stresses will give a better estimate of the peak stress that a lorry gives when passing a stiffener and will include both local and global effects.

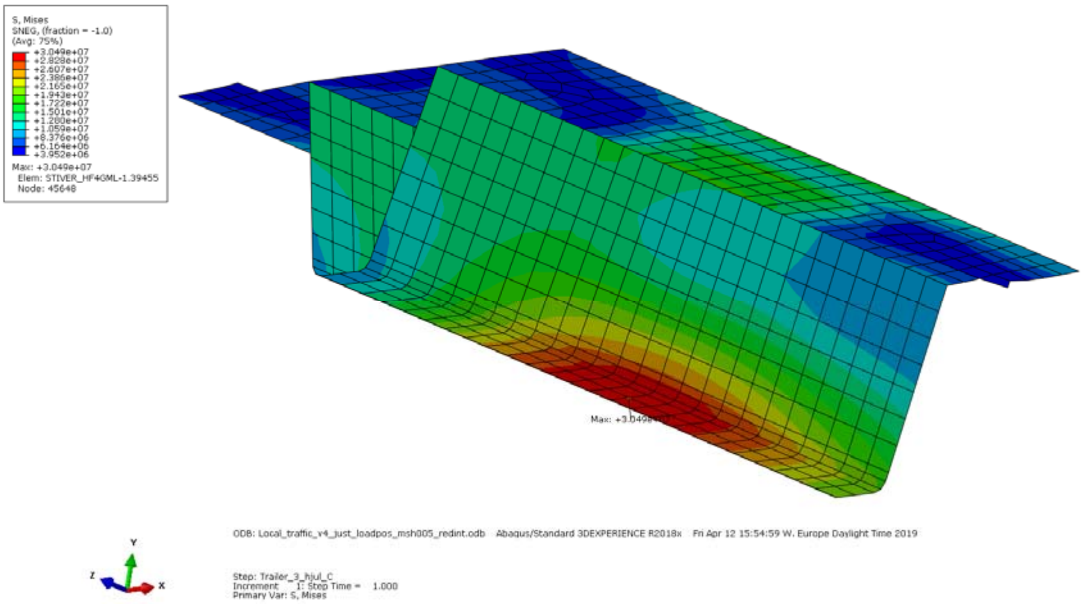


> *Figure 9: Overview of model B*

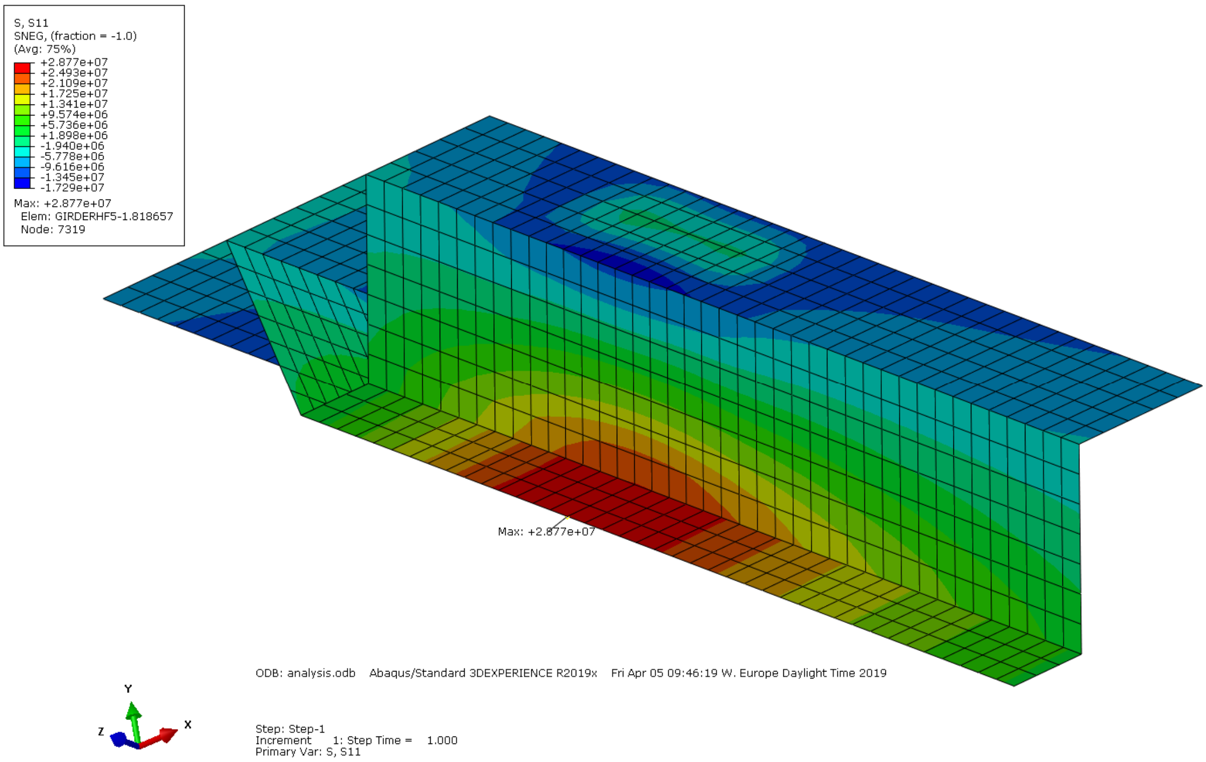


> *Figure 10: Overview of model B. Wheel pressure points shown*

To calculate the most accurate stress range to be used in the combination formula, the ratio between stresses (at bottom of stiffener, in longitudinal direction) in the stiffener found in model B is divided by the stresses found in model A. This will give a scale factor that the local stress ranges for each lorry found in the previous section can be multiplied with to go from local to global stress ranges for a stiffener and hence calculate the stress to be used in the combination formula.



> *Figure 11: Longitudinal stresses in model A, element size 50 mm. Max. stress = 30,5 MPa*

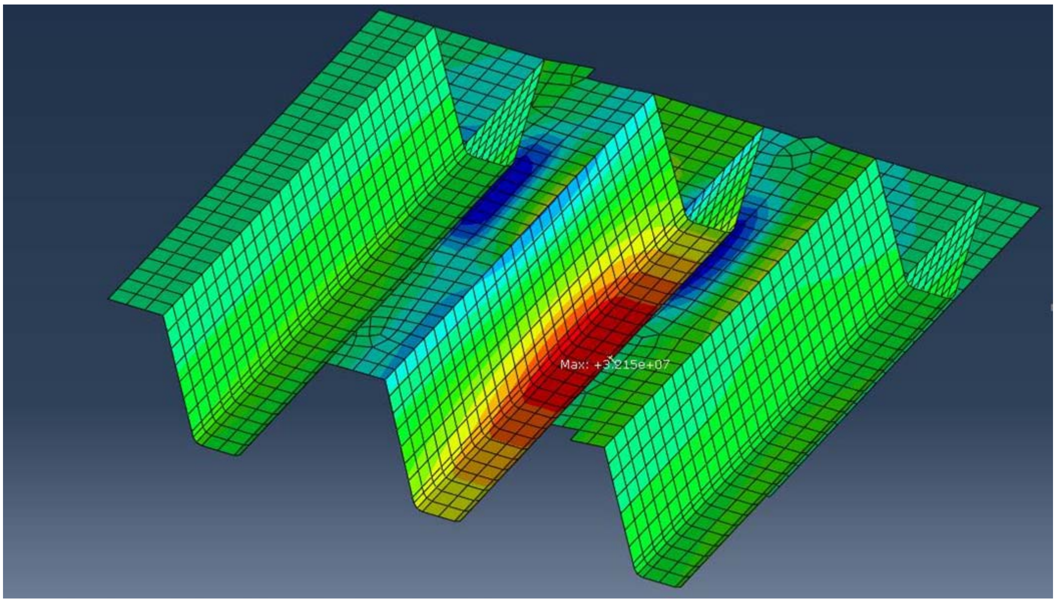


> *Figure 12: Longitudinal stresses in model B. Max. stress = 28,7 MPa*

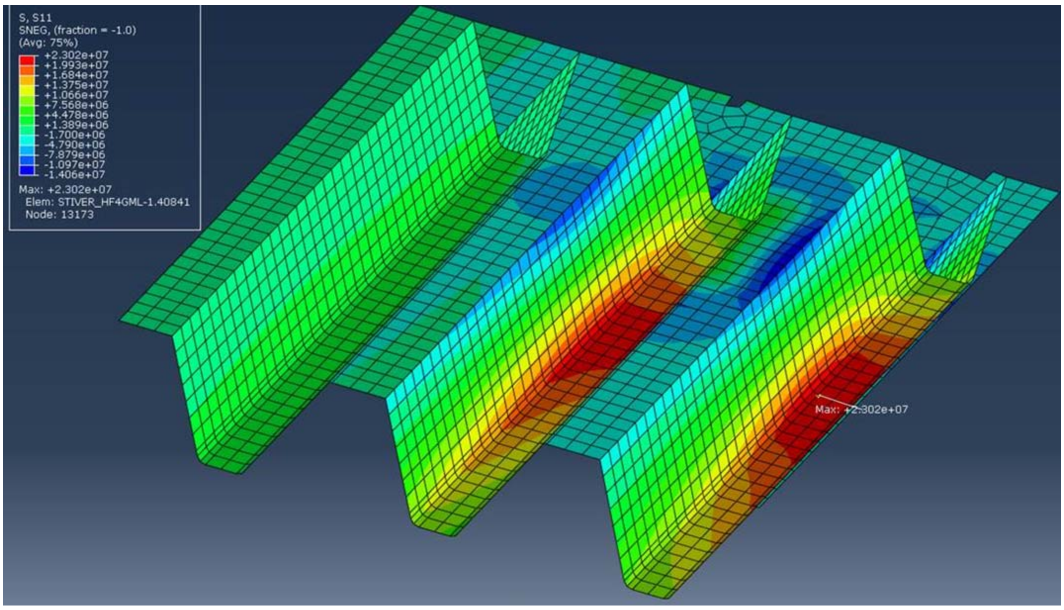
From the figures above a ratio of 28,7/30,5 = 0,94 is found.
This factor may be multiplied with the adjusted stress range shown in Table 1 which yields the stress range to be used in calculation of fatigue life in the mid span for each vehicle. This

procedure is not valid at columns due to the global bending moments being smaller which reduces the effect.
Element size of 15 mm gave a max stress of 32,3 MPa. It is conservatively used a larger mesh size similar to model B.
Global stresses from the traffic analysis in Sofistik can be disregarded (for point B) because this approach yields a more accurate stress range that includes global effects for the critical for the critical point on the stiffener; hotspot 3.

3.3 Study of effect of wheel placement



> *Figure 13: Wheels are placed directly above one stiffener: max stress = 32 MPa*



> *Figure 14 Wheels are placed directly between two stiffeners: max stress = 23 MPa*

Reduction factor on stresses when placing wheels between two stiffeners: 23/32 = 0,72
This factor is included in the design of the welded box stiffeners.