A.1 Matlab script

Calculate compliance during fatigue testing.

Zero the displacement.

If load is increasing, record data.

If load has stopped increasing, stop recording and make a linearization.

Insert linear fit into curve.

Plot load curve, displacement curve and compliance curve.

```
function compliancefatigue(data)
data(:,3)=data(:,3)-data(1,3);
c=[0,0];
k=1;
l=1;
comp=[0,0,0];
length=numel(data(:,2));
for i = 1:length-1
    c=0;
    if data(i+1,2) > data(i,2) & 0.1<data(i,2)
        comp(l,:) = data(i,:);
        l = l+1;
    end

    if data(i+1,2) < data(i,2) & comp(:,1)>0
        if numel(comp(:,2))<2
            c=c;
        else
            c=polyfit(comp(:,2),comp(:,3),1);
        end

        ccurve(k,2)=c(1,1);
        ccurve(k,1)=data(i,1);
        comp=[0,0,0];
        l=1;
        k=k+1;
    end
end
subplot(3,1,1); plot(data(:,1),data(:,2));
title(inputname(1))
legend('Load curve','Location','NorthEast')
xlabel('Time, t [s]')
ylabel('Load, P [kN]')
subplot(3,1,2); plot(data(:,1),data(:,3));
legend('Displacement
curve','Location','NorthEast')
xlabel('Time, t [s]')
ylabel('Displacement, /Delta [mm]')
subplot(3,1,3); plot(ccurve(:,1),ccurve(:,2));
legend('Compliance curve','Location','NorthEast')
xlabel('Time, t [s]')
ylabel('Compliance, C [mm/kN]')
```

A.2 Specimen production

A list of specimens produced for the project report [9]. Abbreviations were used for reference. N is for Needle gun surface preparation. G is for grit blasted surface preparation. C is for pre-cured glass fiber layer. P is for pre-impregnated glass fiber layer, The tests in bold are the ones conducted for this thesis.

Table 1: Full batch of specimens produced

	Precured glass fibre	Pre-preg glass fibre
Needle gun	8x ENF-NC	8x ENF-NP
Grit blasted	8x ENF-GC, **8x ENF-GC-C**	8x ENF-GP

	Precured glass fibre	Pre-preg glass fibre
Needle gun	8x DCB-NC	8x DCB-NP
Grit blasted	8x DCB-GC, **8x DCB-GC-C**	8x DCB-GP

A.3 Quasi-static tests, DCB

Using the relation **Error! Reference source not found.** the average G_{IC} was calculated and a function C (a) found.

Table 2: DCB quasi static tests

Specimen	Cycle	Compliance C [mm/kN]	Crack length, a [mm]	GIC [J/m^2]
7	a	4,67	39,0	529,2
	b	5,53	54,3	682,1
	c	7,15	66,8	776,2
	d	8,74	75,8	798,8
	e	10,31	82,0	866,2
	f	11,20	86,0	919,0
	g	13,34	93,3	934,4
	h	15,36	99,3	912,6
	i	17,50	105,3	929,8
	j	19,77	112,3	895,0
	k	22,43	119,3	836,1
6	a	6,23	39,5	882,2
	b	7,37	59,8	1061,9
	c	9,68	75,3	1033,7
	d	13,51	89,8	1143,9
	e	17,34	105,0	1039,5
	f	25,86	120,5	919,2
	g	33,03	132,8	938,2
	h	44,85	145,3	1094,5
	i	63,35	164,5	1005,5
4	a	6,12	53,5	897,3
	b	7,98	77,5	890,6
	c	11,02	88,5	1077,6
	d	13,18	97,3	952,2
	e	17,18	109,0	1165,4
	f	19,66	116,3	1028,9
	g	24,75	125,5	877,8
	h	30,19	135,0	880,7
	i	36,53	146,5	993,6
	j	45,15	155,5	1157,0

Specimen	Cycle	Compliance C [mm/kN]	Crack length, a [mm]	GIC [J/m^2]
3	a	4,65	36,8	741,2
	b	7,09	53,5	1158,7
	c	7,97	64,0	967,4
	d	10,19	79,0	1012,6
	e	12,95	96,0	866,5
	f	21,21	118,5	817,9
	g	35,94	139,8	796,7
	h	49,12	158,0	599,9
	i	70,65	172,8	665,6
2	a	4,54	53,5	706,0
	b	7,45	74,3	919,1
	c	10,13	86,3	976,8
	d	11,38	96,5	802,7
	e	16,64	107,0	869,5
	f	20,51	118,0	927,1
	g	26,79	129,3	950,4
Average				910,8
Std. Dev				142,6

A.4 Quasi-static tests, ENF

Specimen	#	Crack length, a [mm]	GIC [J/m^2]	Critical load, Pc [kN]
1	a	36	825,15	2,845
	b	32	591,90	2,795
	c	27	805,04	4,127
	d	24	673,30	4,2
2	a	32	387,71	2,17
	b	40	717,09	2,52
3	a	22	508,72	3,562
	b	22	582,77	3,66
	c	22	767,16	4,618
	d	22	868,51	4,92
4	a	27	564,09	3,154
	b	27	933,76	4,306
	c	27	1017,37	4,515
	d	27	1354,51	4,993
5	a	32	724,92	3,08
	b	32	807,96	3,25
	c	32	880,87	3,45
	d	32	1020,17	3,54
6	a	37	477,73	2,06
	b	37	622,86	2,41
	c	37	706,08	2,68
	d	37	694,73	2,62
7	a	42	501,94	1,86
	b	42	710,99	2,13
	c	42	1482,13	2,93
Average			769,10	3,29

Specimen	Cycle	Crack length, a [mm]	Complaince, C [mm/kN]
1	a	12	0,2085
	b	17	0,2072
	c	22	0,1851
	d	27	0,2154
	e	32	0,235
	f	37	0,2581
	g	42	0,2877
	h	47	0,3202
	i	36	0,2516
	j	32	0,2194
	k	27	0,178
	l	24	0,1754
2	a	12	0,1968
	b	17	0,203
	c	22	0,2179
	d	27	0,238
	e	32	0,2524
	f	37	0,2592
	g	42	0,269
	h	47	0,3366
	i	32	0,2393
	j	40	0,2463
3	a	12	0,2138
	b	22	0,214
	c	32	0,2749
	d	22	0,214
	e	22	0,2322
	f	22	0,192
	g	22	0,1915
4	a	17	0,1942
	b	27	0,2127
	c	37	0,261
	d	27	0,2127
	e	27	0,1889
	f	27	0,1872
	g	27	0,2038

Specimen	Cycle	Crack length, a [mm]	Complainte, C [mm/kN]
5	a	22	0,2081
	b	32	0,222
	c	42	0,2829
	d	32	0,222
	e	32	0,2215
	f	32	0,2148
	g	32	0,2364
6	a	27	0,2313
	b	37	0,2667
	c	47	0,3407
	d	37	0,2667
	e	37	0,2548
	f	37	0,2334
	g	37	0,2412
7	a	32	0,2313
	b	42	0,3026
	c	52	0,3407
	d	42	0,3026
	e	42	0,3254
	f	42	0,3579

A.5 Compliance calibrations

Table 3: DCB compliance, quasi-static

Parameter	Value	StdErr	CV(%)
h	-2,26	0,17	7,53
n	1,74	0,09	4,94

Table 4: ENF compliance, quasi-static

Parameter	Value	StdErr	CV(%)
α	1,90E-01	4,27E-03	2,24E+00
β	1,32E-06	8,73E-08	6,59E+00

Table 5: DCB compliance, FE

Parameter	Value	StdErr	CV(%)
h	-3,95E+00	7,00E-02	1,77E+00
n	2,55E+00	3,85E-02	1,51E+00

Table 6: ENF compliance, FE

Parameter	Value	StdErr	CV(%)
α	1,03E-01	7,33E-04	7,10E-01
β	6,58E-07	1,01E-08	1,53E+00

A.6 Fatigue data, DCB tests

#	Pmin	Pmax	da/dN	ΔG	Na	Gmax	f
2e	0,103	0,416	9,05E-03	386	221	398	1 Hz
2f	0,090	0,388	2,62E-03	338	855	347	1 Hz
2g	0,077	0,375	3,43E-03	288	550	294	1 Hz
2i	0,064	0,359	2,67E-03	269	785	274	1 Hz
2j	0,063	0,375	1,51E-03	287	443	292	1 Hz
2k	0,058	0,350	2,92E-03	269	949	274	1 Hz
2m	0,033	0,324	1,06E-03	347	1222	351	1 Hz
2n	0,041	0,335	1,64E-03	369	735	374	1 Hz
2o	0,061	0,392	2,70E-02	470	74	478	1 Hz
2p	0,054	0,381	7,54E-03	461	311	467	1 Hz
2q	0,049	0,384	7,73E-03	500	181	506	1 Hz
2r	0,042	0,363	3,53E-03	476	243	481	1 Hz
2s	0,039	0,350	4,26E-03	476	302	482	1 Hz
2t	0,036	0,346	7,69E-03	494	134	499	1 Hz
2u	0,039	0,342	2,01E-02	506	30	512	1 Hz
2v	0,035	0,355	1,43E-02	548	78	554	1 Hz
2w	0,029	0,352	2,88E-02	567	113	571	1 Hz
2x	0,027	0,360	3,49E-02	607	56	612	1 Hz
2y	0,026	0,364	1,65E-02	633	53	637	1 Hz
2z	0,023	0,349	1,46E-02	619	96	623	1 Hz
2aa	0,028	0,353	2,90E-02	649	63	654	1 Hz
2ab	0,026	0,344	1,12E-02	645	63	650	1 Hz
2ac	0,024	0,320	3,05E-02	591	20	596	1 Hz
2ad	0,023	0,318	1,02E-02	608	53	612	1 Hz
2ae	0,019	0,290	3,70E-02	580	138	584	1 Hz
2af	0,017	0,296	3,26E-02	513	48	516	1 Hz
2ag	0,016	0,289	1,26E-02	610	81	614	1 Hz
2ah	0,014	0,267	1,89E-02	572	149	575	1 Hz
2ai	0,011	0,257	1,08E-02	560	128	562	1 Hz

#	Pmin	Pmax	da/dN	ΔG	Na	Gmax	f
3b	0,037	0,280	9,90E-04	188	2021	192	1 Hz
3c	0,055	0,267	9,01E-03	176	444	181	1 Hz
3d	0,017	0,441	2,00E+01	559	1	561	1 Hz
3e	0,018	0,393	1,13E-01	172	62	174	1 Hz
3f	0,011	0,349	1,69E-02	291	237	292	1 Hz
3g	0,004	0,302	1,11E-02	334	452	334	1 Hz
3h	0,001	0,279	0,00E+00	287	222	287	1 Hz
3i	0,001	0,273	1,55E-03	282	1288	282	1 Hz
3j	0,001	0,244	4,03E-04	246	1697	246	1 Hz
3k	0,008	0,245	1,20E-03	246	2186	247	1 Hz
3l	0,001	0,207	4,08E-04	193	2450	194	1 Hz
3m	0,000	0,199	9,96E-05	182	5736	182	1 Hz
5a	0,050	0,417	2,90E+01	794	16	805	1 Hz
5b	0,039	0,381	2,28E-02	415	78	419	1 Hz
5c	0,055	0,294	1,78E-03	253	1684	264	1 Hz
5d	0,048	0,275	8,75E-04	228	3253	237	1 Hz
5e	0,062	0,195	2,32E-05	95	43160	95	4Hz
6a	0,084	0,288	4,64E-03	194	2156	210	4Hz
6b	0,088	0,276	4,39E-04	146	4560	160	4Hz
6c	0,065	0,259	2,80E-05	132	19440	141	4Hz
6d	0,041	0,229	1,63E-05	112	29044	117	4Hz
6e	0,018	0,1931	2,295E-06	105	435760	106	4Hz
6f	0,015	0,1849	2,649E-06	86	236000	88	4Hz

A.7 Fatigue data, ENF tests

#	Pmin	Pmax	a	N	ΔG	C
Load control						
1a	-2,28	-0,23	22	640	210,20	0,14
1a	-2,28	-0,23	22	2400	203,13	0,14
1b	-2,29	-0,23	22	7955	256,81	0,17
2a	-2,28	-0,23	32	182	786,61	0,32
2b	-2,47	-0,25	29	139	434,96	0,17
2c	-2,28	-0,23	27	2992	350,28	0,18
2c	-2,28	-0,23	47	500	628,30	0,19
3a	-1,77	-0,18	12	2499	47,07	0,18
3b	-1,76	-0,18	22	3999	145,12	0,17
3b	-1,76	-0,18	27	10000	220,63	0,17
3b	-1,76	-0,18	37	5000	419,86	0,17
3c	-1,77	-0,18	22	4580	163,84	0,19
4a	-2,64	-0,26	22	120	369,99	0,18
4b	-2,47	-0,25	22	450	286,98	0,16
5b	-1,33	-0,13	32	650	179,35	0,21
5b	-1,33	-0,13	43	600	242,25	0,21
5b	-1,33	-0,13	45	900	258,49	0,22
5b	-1,33	-0,13	55	1600	287,64	0,23
5b	-1,33	-0,13	61	2800	302,35	0,25
5c	-0,96	-0,10	32	15900	116,80	0,26
5c	-0,96	-0,10	32	123000	122,64	0,27
Displacement control						
6b	-1,73	0,00	22	7100	164,16	0,19
6b	-1,68	0,00	22	33800	165,80	0,20
7a	-1,75	0,00	22	40	199,45	0,22
7b	-1,28	0,00	22	26350	93,74	0,20
7b	-1,28	0,00	22	88000	99,59	0,21
7c	-0,95	0,00	22	1200	67,83	0,26
7c	-0,88	0,00	22	3500	61,34	0,27

A.8 Fatigue parameter, curve fit

To find the parameters from the GN curves, linear fits are found for the G vs N plots in logarithmic scale. The parameters are acquired starting with:

$$\log(\Delta G) = \mathrm{m}_2 \log(N) + m_1$$
$$C_1 = \frac{1}{10^{m_1}}$$
$$C_2 = \frac{1}{m_2}$$

Likewise for the da/dN-curve:

$$\log\left(\frac{da}{dN}\right) = m_4 \log(\Delta G) + m_3$$
$$C_3 = 10^{m_3}$$
$$C_4 = m_4$$

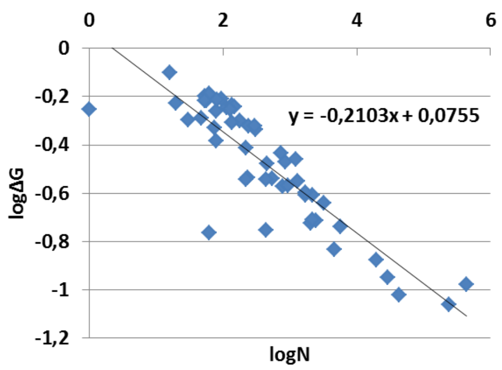


Figure 1: G-N curve fit, DCB

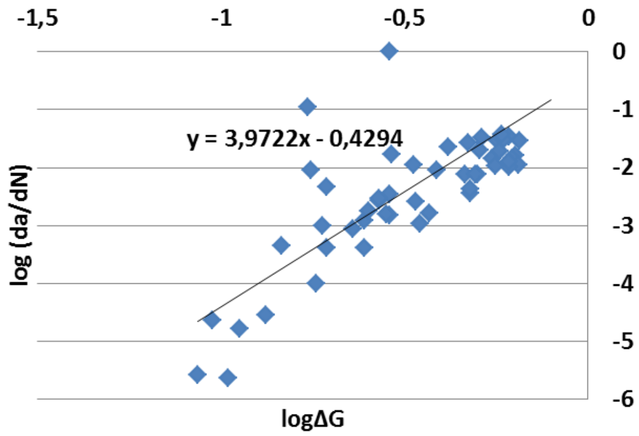


Figure 2: Crack propagation rate, curve fit, DCB

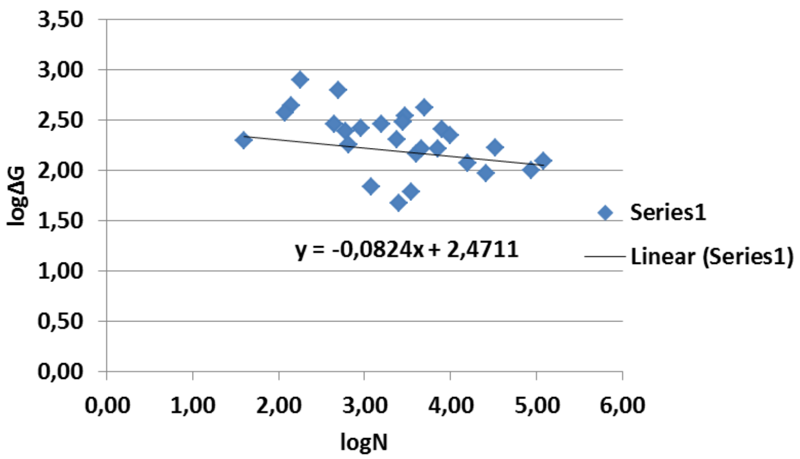


Figure 3: G-N curve fit, ENF

A.9 Fatigue parameters

Table 7: LCF Criterion Parameters, ENF

G-N constants, ENF	
C1	0,736
C2	-5,945

Table 8: LCF Criterion Parameters, DCB

G-N constants, DCB		**Paris' constants, DCB**	
C1	0,840	C3	0,372
C2	-4,755	C4	3,972

B. Simulation procedure

B.1 Simulation parameters

Table 9: LCF Criterion Parameters, DCB

G-N constants, DCB		Paris' constants, DCB	
C1	0,840	C3	0,372
C2	-4,755	C4	3,972

Table 10: Direct Cyclic Step Parameters

Direct cyclic step	**Fatigue**		
Cyce time period	1		
Max number of increments	100000		
Increment size	0,1		
Max number of iterations	5		
Number of fourier terms	Initial 25	Max 25	Increment 5
Cycle increment size	Min 10	Max 100	
Maximum number of cycles	100000		
Damage extrapolation tolerance	1		

Table 11: Amplitude Parameters

Parameters amplitude	
ω	6,28
A0	d_mean
A1	d_amp
t0	0

Table 12: VCCT Parameters

Parameters VCCT	
GIC	0,91
GIIC	0,769
GIIIC	0,769
η	2,284

B.2 Benchmark element size

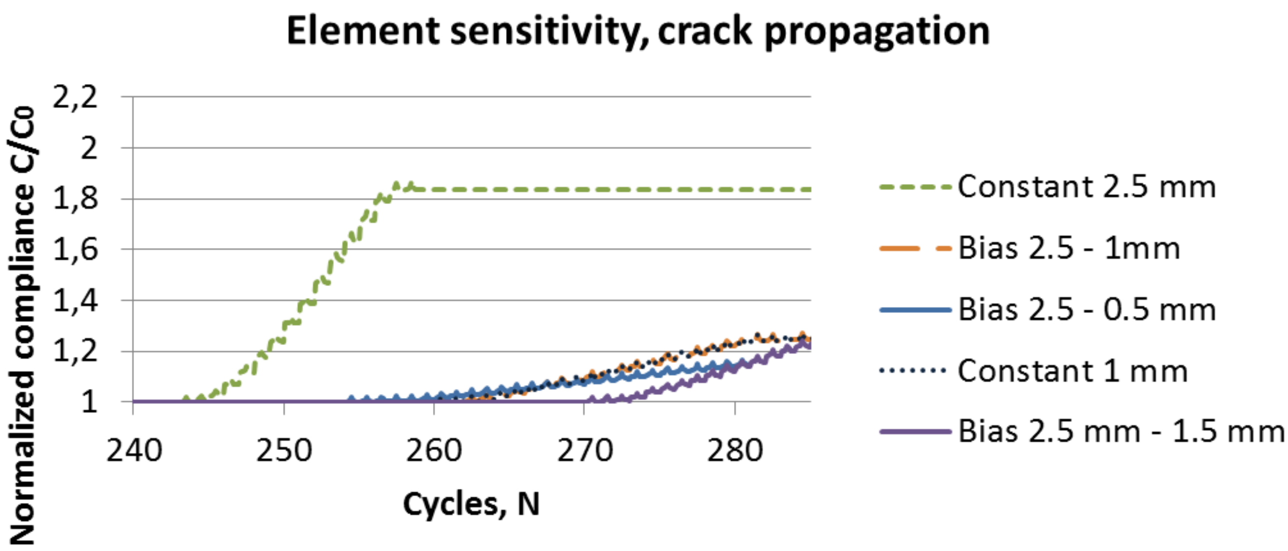


Figure 4: Element sensitivity, crack propagation of ENF

Tests done using a cyclic displacement δ_{max} = 0.45 and δ_{min} = 0.048 on ENF with 10 elements in width and a decrease in element length at the crack front. There is complete overlap for biased and constant element length of 1 mm. The constant element length of 2.5 mm estimates an earlier and longer fracture. The element lengths of 1 mm and lower are computationally expensive.

B.3 Load curve comparison, ENF

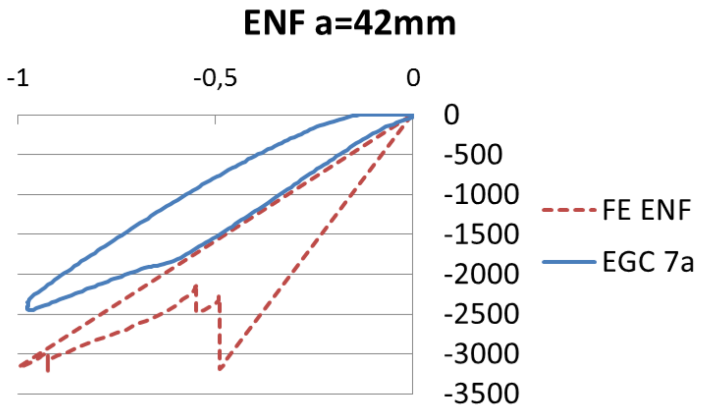


Figure 5: Load curves comparison of FE-model and a specimen of equal crack length

B.4 Cohesive Zone Modelling

A way of modelling crack propagation in a known direction such as adhesive interfaces or delamination, is cohesive zone modelling, CZM. This uses a set of cohesive elements, which are bonding elements between two surfaces of solid element instances. When the elements are strained, they lose stiffness by the formula

$$t_i = (1-d)K_i\delta_i \tag{0.1}$$

Here t_i is traction, d is the damage variable, which has the value d = 0 when the interface is undamaged, and the value d = 1 when the interface is fully fractured. Fully degraded elements are fully compliant and take up no forces in the structure in further increments. As elements are fully degraded, they are deleted so as to not cause slow simulations due to large time increment estimations as recommended by Diehl [37].

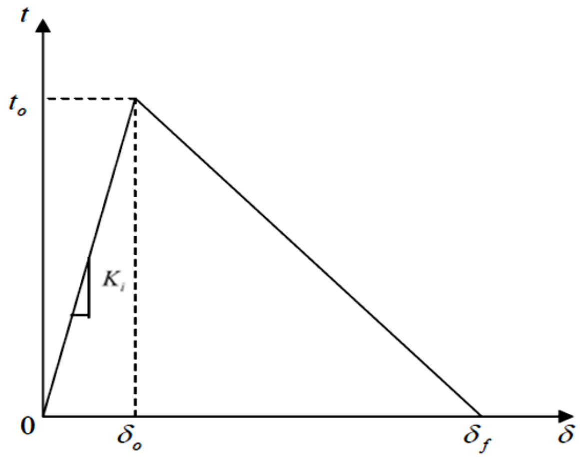


Figure 6: Traction-separation law

The controlling parameters for the critical strain, are the energy release rate, G_c, the interface strength S_i which is the maximum stress of the bond and the traction-separation relation [38]. Although data for the epoxy strength and stiffness are given by the supplier, the same values at the interface are likely to differ. A proposed way of calculating interface strength is

$$S_i = \frac{2G_i}{\delta_f} \tag{0.2}$$

The cohesive stiffness K_i is the individual stiffness of each element and was defined by Diehl as [38]

$$K_i = \frac{2G_i}{\delta_{ratio}(\delta_f)^2} \tag{0.3}$$

The total stiffness is dependent on the size of the elements. For the analysis used in chapter **Error! Reference source not found.**, an element size of 1 mm was used, a failure displacement of 0.3 and the stiffness and strength were adjusted accordingly. This model may only be used on other geometries provided that the same production method and bond thickness is attained.

C. Setup

C.1 Steel characterization tests

Tests were done using an Instron 100kN machine. The specimens were not machined and retained the geometries of 25 mm x 250 mm. Strain gauges were placed on the middle of each specimen. Specimens were loaded at a rate of 0.3mm/min for loads under 25kN. After 25kN, plasticity was certain and load rate was increased to 5mm/min until fracture occurred. For E-modulus, the specimens were loaded three times within elastic area.

<table>
<tr><th rowspan="2">Specimen</th><th rowspan="2">Width [mm]</th><th rowspan="2">Thickness [mm]</th><th rowspan="2">Cross-sectional area [mm^2]</th><th rowspan="2">Cycle</th><th colspan="4">Modulus of Elasticity [MPa]</th></tr>
<tr><th colspan="2">Extensometer</th><th colspan="2">Strain gauge</th></tr>
<tr><td rowspan="3">9TC</td><td rowspan="3">25,60</td><td rowspan="3">5,07</td><td rowspan="3">129,69</td><td>1</td><td colspan="2">186 448</td><td colspan="2">211 945</td></tr>
<tr><td>2</td><td colspan="2">186 397</td><td colspan="2">208 787</td></tr>
<tr><td>3</td><td colspan="2">186 159</td><td colspan="2">209 925</td></tr>
<tr><td rowspan="3">14TP</td><td rowspan="3">26,02</td><td rowspan="3">5,04</td><td rowspan="3">131,14</td><td>1</td><td colspan="2">184 223</td><td colspan="2">200 918</td></tr>
<tr><td>2</td><td colspan="2">184 068</td><td colspan="2">201 443</td></tr>
<tr><td>3</td><td colspan="2">183 494</td><td colspan="2">198 494</td></tr>
<tr><td colspan="5">Mean Transverse</td><td>185 131</td><td>1 344</td><td>205 252</td><td>5 623</td></tr>
<tr><td rowspan="3">4LC</td><td rowspan="3">25,41</td><td rowspan="3">5,09</td><td rowspan="3">129,42</td><td>1</td><td colspan="2">175 123</td><td colspan="2">224 832</td></tr>
<tr><td>2</td><td colspan="2">176 362</td><td colspan="2">225 229</td></tr>
<tr><td>3</td><td colspan="2">186 407</td><td colspan="2">225 008</td></tr>
<tr><td rowspan="3">16LP</td><td rowspan="3">25,90</td><td rowspan="3">5,02</td><td rowspan="3">129,93</td><td>1</td><td colspan="2">209 153</td><td colspan="2">206 439</td></tr>
<tr><td>2</td><td colspan="2">181 905</td><td colspan="2">216 648</td></tr>
<tr><td>3</td><td colspan="2">179 057</td><td colspan="2">216 912</td></tr>
<tr><td colspan="5">Mean Longitudinal</td><td>184 668</td><td>12 663</td><td>219 178</td><td>7 435</td></tr>
</table>

Table 13: E-modulus, steel tests

Position		Specimen	Width [mm]	Thickness [mm]	Cross-sectional area [mm^2]	Yield Strength [MPa]	Tensile strength [MPa]
Transverse	Center	1TC	25,34	5,08	128,64	389,80	443,79
		2TC	25,24	5,04	127,23	392,90	451,27
		10TC	25,24	5,03	126,96		
		Sub-mean	-	-	-	391,35	447,53
	Side	5TS	25,71	5,06	130,09	407,30	450,74
		6TS	25,18	5,08	127,85	395,90	444,62
		13TP	25,75	5,03	129,52	385,60	448,75
		Sub-mean	-	-	-	396,27	448,03
Longitudinal	Center	3LC	25,48	5,06	128,83	381,50	446,53
		4LC	25,41	5,09	129,42		
		11LC	25,28	5,08	128,41	377,20	448,37
		Sub-mean	-	-	-	379,35	447,45
	Side	7LS	25,18	5,06	127,41	394,20	463,29
		8LS	25,28	5,05	127,68	386,50	448,26
		15LP	25,78	5,01	129,06	385,50	450,99
		Sub-mean	-	-	-	388,73	454,18
Total						389,64	449,66

Table 14: Yield and tensile strength, steel tests

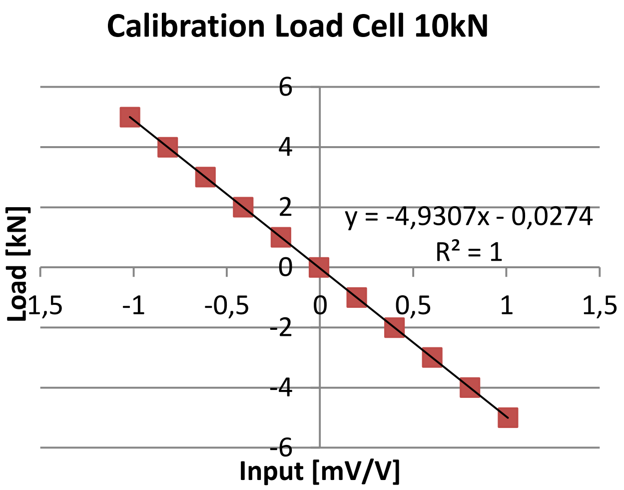
On 14TP and 16LP strain gauges were placed transverse of length direction to attain the Poisson's ratio by the formula $= -\frac{\varepsilon_2}{\varepsilon_1}$.

Poisson's ratio		
16LP	0,319	
	0,338	
	0,338	
Sub-mean	0,332	0,011
14TP	0,269	
	0,265	
	0,267	
Sub-mean	0,267	0,002
Mean	0,299	0,036

Table 15: Poisson's ratio, steel tests

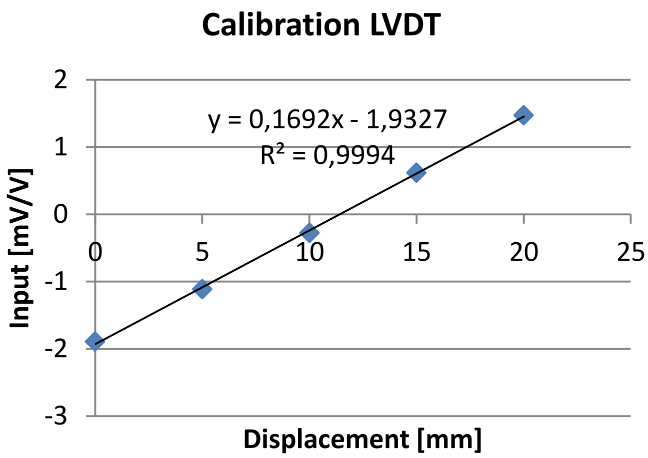
C.2 Equipment calibration

Externally applied load cell and LVDT were calibrated and checked for linearity.



Calibration Load cell	
mv/V	kN
-1,0194	5
-0,81648	4
-0,6144	3
-0,41172	2
-0,20844	1
-0,00528	0
0,19816	-1
0,3996	-2
0,60264	-3
0,80532	-4
1,00896	-5

Figure 7: Calibration load cell



Calibration LVDT	
mv/V	Displ.
1,4712	20
0,6136	15
-0,28	10
-1,114	5
-1,8948	0

Figure 8: Calibration LVDT