Tests on Turnlok (TM) System Scaffold Components

for VR Access Solutions Ltd

Report No 407

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April 2016

Contents

1. Introduction

This report describes a range of tests carried out on connections and braces for VR Access Systems Ltd Scaffold Components.

This series of tests was carried out generally in accordance with the recommendations contained in BS EN12811-3~2002 entitled “Temporary works equipment Part 3 Load testing”.

The following tests were made:

- Cyclic load tests on ledger/transom to standard connections
- Vibration tests on ledger /transom to standard connections
- Cyclic load tests on façade bracing.
- Tensile tests

The tensile tests were made on samples cut from the test pieces in order to be able to adjust the test results back to the specified minimum yield strengths and to establish the mechanical properties of the tested components where such adjustments are not practicable.

2. Cyclic tests on ledger/transom to standard connections

The test arrangement for these tests is shown in Figure 1. Figure 2 shows a transom-standard test where the load and the corresponding rotation are taken to be positive. The arrangement for negative loading and rotation is shown in Figure 3.

In these assemblies the standard was clamped to a rigid support and a ledger/transom attached to it. The load was applied hydraulically on a line 400mm from the centreline of the standard. The ledger/transom was set between greased guides to ensure vertical displacement only. In all the cyclic tests on ledgers and transoms loading was conducted under displacement control at a rate of 0.2 mm per second with a sampling rate of 1 sample per second. The rotation of the ledger relative to the standard was measured by observing the difference in the movement of two displacement transducers mounted 50mm apart on a bracket fixed to the ledger.

Four pilot tests, two in the positive direction (J646LLFN, J646TLFN) and two in the negative direction (J646LLFI, J646TLFI), were made on the connection to give an estimate of the characteristic moment. The results of these tests have been plotted in Appendix 2, Section (a). Note that the convention used in the testing sequence for specimens was to define specimens under positive rotation to be testing in the ‘normal configuration’ and for specimens tested under negative rotation to be testing in the ‘inverted configuration’.

These graphs show that the connection is a little weaker and less stiff in the positive direction when compared with the negative direction of loading. However, its initial slope was approximately the same in both directions.

Based on the pilot tests each of the three test samples was tested by loading cyclically three times before loading to failure. The loading regime for the ledger/transom – standard connections and the brace assemblies is given in Table 1.

Test	Unload at	Number of tests
Ledger, positive rotation	6 kN (compression) 5.6 kN (tension)	3 cycles, then to failure in the positive direction
Ledger, negative rotation	5.6 kN (tension) 6 kN (compression)	3 cycles, then to failure in the negative direction
Transom, positive rotation	5.5 kN (compression) 4.2 kN (tension)	3 cycles, then to failure in the positive direction
Transom, negative rotation	4.2 kN (tension) 5.5 kN (compression)	3 cycles, then to failure in the negative direction
Bracing assembly, brace in compression	14.7 kN (compression) and 17 kN (tension)	3 cycles, then to failure in the positive direction
Bracing assembly, brace in tension	17 kN (tension) and 14.7 kN (compression)	3 cycles, then to failure in the negative direction

Table 1. Summary of the cyclic loading regime.

For the ledger to standard connection, the modes of failure were primarily due to distortion/splitting of the cup and tongue fracture. See Figure 4.

For the transom to standard connection, the modes of failure were primarily due to distortion/splitting of the cup and tongue bending/fracture. See Figure 5.

A tabulation of the failure modes for each test is given in Appendix 1.

In Figure 6 all the ledger to standard cyclic tests are plotted on a single graph. The figure shows some variation between one test and another, and confirms that the connection is a little stronger in the negative direction. Detailed moment-rotation curves are set out in Appendix 2, Section (b). Note that the negative direction results have been shown positive in the appendix for simplicity. A polynomial approximation to the loading curve has been superimposed on each test result, displaced so that it passes through the origin. This curve is used later in the treatment of the results and its equation is given on the graph.

In Figure 7 all the transom to standard cyclic tests are plotted on a single graph. The figure shows some variation between one test and another, particularly under negative rotation. As can be seen the transom has high variability in the maximum moment in the negative or inverted direction which accounts for the low characteristic and service moments in this direction although the section is stiffer under these moments. Detailed moment-rotation curves are set out in Appendix 2, Section (c). Note that the negative direction results have again been shown positive in the appendix for simplicity.

3. Tests on bracing assemblies

Tests on bracing assemblies were carried out to determine the strength, stiffness and looseness of the façade bracing.

The test assembly for the bracing comprised a braced frame made up of standards and ledgers and two façade bracing members. One bracing member was attached to each side of the standards using the normal coupling to ensure symmetry. A sketch of the arrangement showing the overall dimensions is shown in Figure 8.

During the test the load was applied to one of the standards on the left of the test assembly and the deflection was measured in two places on the right side of the assembly to allow the calculation of the shear deflection of the braced panel. Two displacement transducers were positioned at each measuring point, symmetrically placed about the centreline of the standard so that any twist of the upright could be eliminated. The positions of the load and the points at which the displacements were measured are given in Figure 9. Figure 9 shows the point of application of the load below the intersection of the diagonal and the other two members. It was not possible to apply the load directly to the intersection.

Figures 10 and 11 are a general view of the test arrangements for tension and compression, partially obscured by the straining frames. The test frame was founded on two pin bearings which were bolted to the support frame to provide horizontal resistance to the applied loads.

Two pilot tests were made on the bracing assembly to determine the approximate maximum loads, one with the braces in tension and the other with the braces in compression. In the tension test the maximum load reached was about 50 kN. In the test the standard distorted and there was brace movement. In the second pilot test the maximum load was approximately 40 kN at which point the bolt sheared. The load-deflection curves for the pilot tests are shown in Appendix 3, Section (a). The loading rate was set at 0.2 mm/sec with a sampling rate of 0.5 seconds. Note that in calculations for maximum load the test applied load was divided by 2 as two braces were tested simultaneously to avoid distortion due to eccentricity.

The assembly was loaded in one direction only as there were two bracing connections, one putting the fixing connection into compression and the other, at the other end of the diagonal, putting the connection into tension. Thus failure in the test would be due to failure of the weaker of the two end connections. The test setup was such that the diagonals were in either in compression or tension at the point of failure.

The loading regime for the bracing cyclic tests is given in Table 1. Failure of the bracing assembly occurred when the pivot pin at the end of the diagonal twisted and started to pull from its mounting or the uprights bent. Examples of failure modes are given in Figures 12-14.

The complete set of load-deflection curves is shown for the cyclic tests on the bracing assembly in Figure 15. Note that these curves show the total load measured on and applied to the assembly of a pair of façade braces. The load shown is therefore twice that applied to one façade brace.

Detailed load-deflection curves are set out in Appendix C.

4. Vibration tests

A set of three vibration tests was made on transom assemblies arranged in the same manner as the cyclic tests. This is the normal arrangement for the ledger or transom connection
The connection was loaded at ±0.5k N (equal to a moment of 0.20kNm), rather more than 10% of the service load recommended by section 7.4 of BS EN1281 1-3. The connection was subjected to 6200 cycles at 5Hz. In none of the three tests was any indication of loosening of the locking cup observed. Full details summarised in Appendix 4.

5. Tensile tests

The tensile tests were conducted by Westmoreland Mechanical Testing & Research Limited and the results are attached as Appendix 6. Appendix 5 summarises the results to obtain characteristic UTS values.

All test results must be adjusted so that the design values derived from the tests correspond to the minimum mechanical properties for the components concerned. A summary of the tensile and hardness test results has been abstracted from Appendix 4 and is given in Table 2. The ultimate tensile strength for the material was calculated from the hardness test results and where necessary, this is used instead of the yield stress to adjust the test results. The adjustment ratio was calculated using the minimum proof strength of the material. Note that where the measurements are below the minimum guaranteed by the manufacturer, there may be no upwards adjustment of the test results, so that the adjustment ratio is unity, as in the case of the bracing tube.

Item	Tensile test/hardness test	Tensile strength N/mm^2	Standard deviation N/mm^2	Characteristic strength N/mm^2	Adjustment ratio
Tubes	Tensile test	564.3	10.5	532.1	0.958
Bolt	Hardness test	647.0	30.1	559.4	1.000
Bottom cup	Hardness test	657.9	37.2	550.2	1.000
Top cup	Hardness test	655.8	7.9	631.3	1.000
Ledger tongue	Hardness test	543.6	7.0	521.8	0.997
Weld	Hardness test	574.1	99.4	337.0	1.000
Rosette (brace)	Hardness test	157.2	17.0	120.3	1.000

Table 2: Summary of results of tensile tests

Where appropriate an adjustment has been made to the test results using the reduction factor given in the final column of Table 2.

6. Analysis of the test results.

For all the cyclic tests the loading curves were plotted out and the looseness was measured by fitting a straight line to points on the moment-rotation/load-deflection graph in accordance with the arrangement in Figure 4 of BS EN 12811-3. A polynomial approximation to the final loading curve was fitted and the slope of the unloading curve measured from the experimental values.

The ductility of each test assembly was assessed by calculating values of areas under the loading and unloading curves, E_{1o} and E_{ul}, either to correspond with a value of $q_e = 11$, or, when this was not possible, finding the maximum value of q_e by trial and error. In former case, the ultimate load for the test was determined by the point corresponding to the calculated value of $q_e = 11$ and in the latter case, when $q_e < 11$, q_e was determined at the failure point on the graph.

The values of q_e so obtained were averaged and the value of γ_{r2} calculated according to equation 5 in 10.5 of BS EN1281 1-3. The characteristic value of the moment $R_{k,b}$ was obtained using the maximum calculated values corresponding to values of q_e and applying a statistical adjustment to obtain the 5% fractile value. This was then adjusted to take account of their actual mechanical properties of the tested samples as described in Section 6 above. The nominal value of the moment $R_{k,nom}$ is obtained by dividing this by γ_{R2} and the service value by dividing this in turn by γ_f x γ_m .

The initial stiffness of the connection is the harmonic mean of the line between the origin and the service load or moment (secant stiffness) and the unloading curve on the mean moment-rotation or load-deflection curve. The second stiffness is the slope of the secant between the service moment and the characteristic load or moment.

There was significant looseness in all of the test assemblies. This was determined by fitting straight lines through the experimental data. Two values of looseness are given. The first is the average original looseness obtained from the experimental graphs and the second is the total looseness including the original and the additional looseness as defined in EN12811-3.

A summary of all the results is given in Table 3.

In Figures 16, 17 and 18 the design lines and the mean polynomial curves are plotted for the ledger/transom connections and the façade brace. The polynomial equation for each assembly is given in Table 4. In each graph the design characteristic is tri-linear. The first line has a slope equal to the design stiffness, the second the final stiffness and the third is the characteristic force or moment. The first two lines meet on the polynomial curve at the service force or moment and the maximum design moment.

Property	units	Ledger		units	Transom		units	Bracing assembly	
		normal	Inverted		normal	Inverted		compression	tension
q_e mean		10.6221	9.4474		9.1706	5.4166		4.0893	9.3141
γ_{R2}		1.0094	1.0388		1.0457	1.1396		1.1728	1.0422
char $R_{k,nom}$	kNm	3.4220	3.6013	kNm	2.4014	1.6765		15.502	18.748
rot($R_{k,nom}$)	rad	0.1053	0.0872	rad	0.0498	0.0384	def mm	18.761	19.114
service ($R_{k,nom}$)	kNm	2.0546	2.1826	kNm	1.3917	1.0161	kN	9.424	11.362
rot(service)	rad	0.0437	0.04516	rad	0.0342	0.0287	def mm	14.773	16.494
initial slope	kNm/rad	69.621	74.259	kNm/rad	97.596	86.794	kN/mm	6.2210	3.9600
final slope	kNm/rad	21.651	33.751	kNm/rad	57.908	68.139	kN/mm	1.9205	3.5232
unloading slope	kNm/rad	128.56	111.580	kNm/rad	140.882	108.460	kN/mm	8.2368	3.6190
mean looseness	rad	0.0142	0.0155	rad	0.0199	0.0169	mm	16.042	17.250
Total looseness	rad	0.0210	0.03809	rad	0.0221	0.1807	mm	16.930	16.709

Table 3: Summary of design properties

	x^6	x^5	x^4	x^3	x^2	x^1	x^0
Ledger normal	$1.6169*10^6$	$-1.0889*10^6$	$2.7272*10^5$	$-2.9546*10^4$	$8.9422*10^2$	$7.0651*10^1$	$-1.1046*10^0$
Ledger inverted	$1.7066*10^6$	$-1.2628*10^6$	$3.5360*10^5$	$-4.4877*10^4$	$2.1428*10^3$	$3.6582*10^1$	$-9.5431*10^{-1}$
Transom normal	$8.3216*10^4$	$6.3817*10^4$	$-6.9681*10^4$	$2.1403*10^4$	$-3.0655*10^3$	$2.2102*10^2$	$-3.3430*10^0$
Transom inverted	$-2.9234*10^6$	$1.2949*10^6$	$-2.2451*10^4$	$2.3021*10^4$	$-2.0446*10^3$	$1.5302*10^2$	$-2.1100*10^0$
Bracing compression	$-6.6841*10^{-7}$	$1.8526*10^{-4}$	$-8.6462*10^{-3}$	$3.3307*10^{-1}$	$-7.1773*10^0$	$8.2717*10^1$	$-3.8465*10^2$
Bracing Tension	$4.1953*10^{-6}$	$-5.7517*10^{-4}$	$3.2840*10^{-2}$	$-9.9454*10^{-1}$	$1.6608*10^1$	$-1.4020*10^2$	$4.5542*10^2$

Table 4: Coefficients of the moment- rotation and force deflection curves.

7. Conclusions.

This report describes a series of tests made on the VR Access System Ltd Scaffold Components connections and braces in accordance with the recommendations of BS EN 12811-3. The output of the report is the set of structural parameters set out in Table 3, the polynomial coefficients in Table 4 and the graphs in Figures 15, 16 and 17.

Figures

Figure 1: Connection Test arrangement

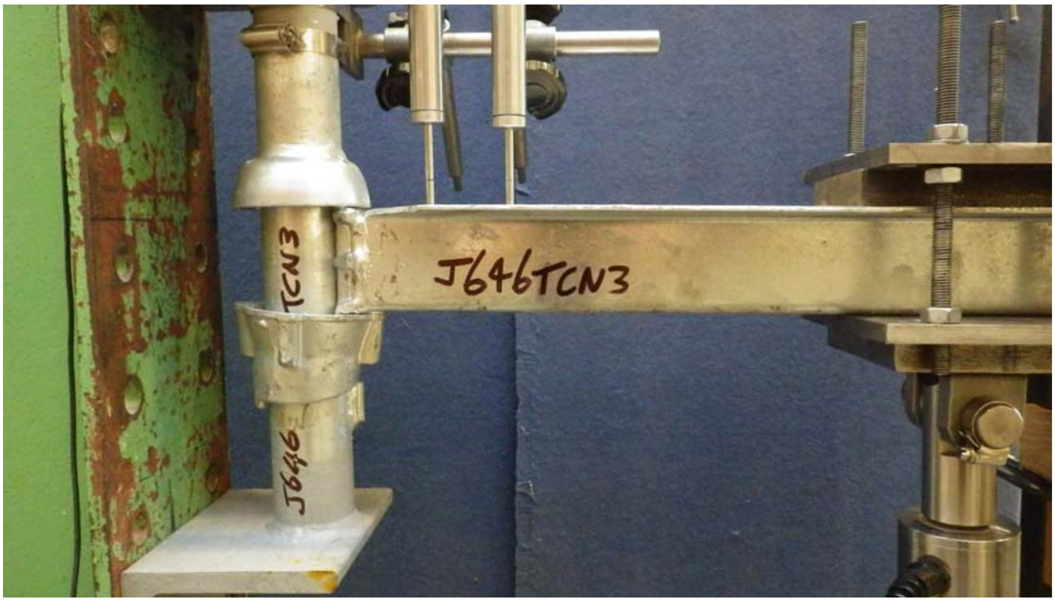


Figure 2: Transom to standard connection test arrangement (positive rotation)

Figure 3: Ledger to standard connection test arrangement (negative rotation)

Figure 4: Cup split and tongue fracture

Figure 5: Weld and tongue fracture

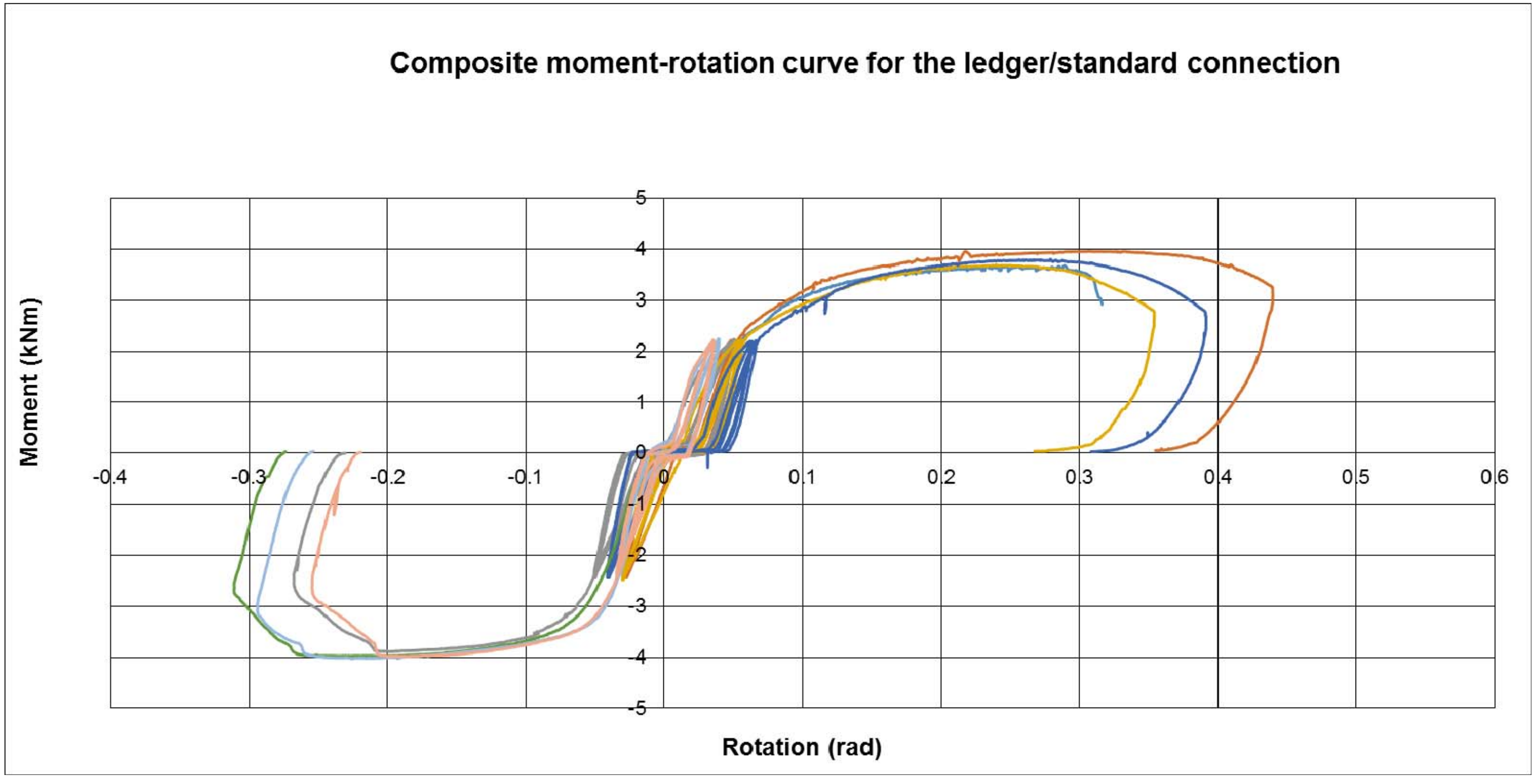


Figure 6: Moment-rotation curves for all ledger - standard cyclic tests

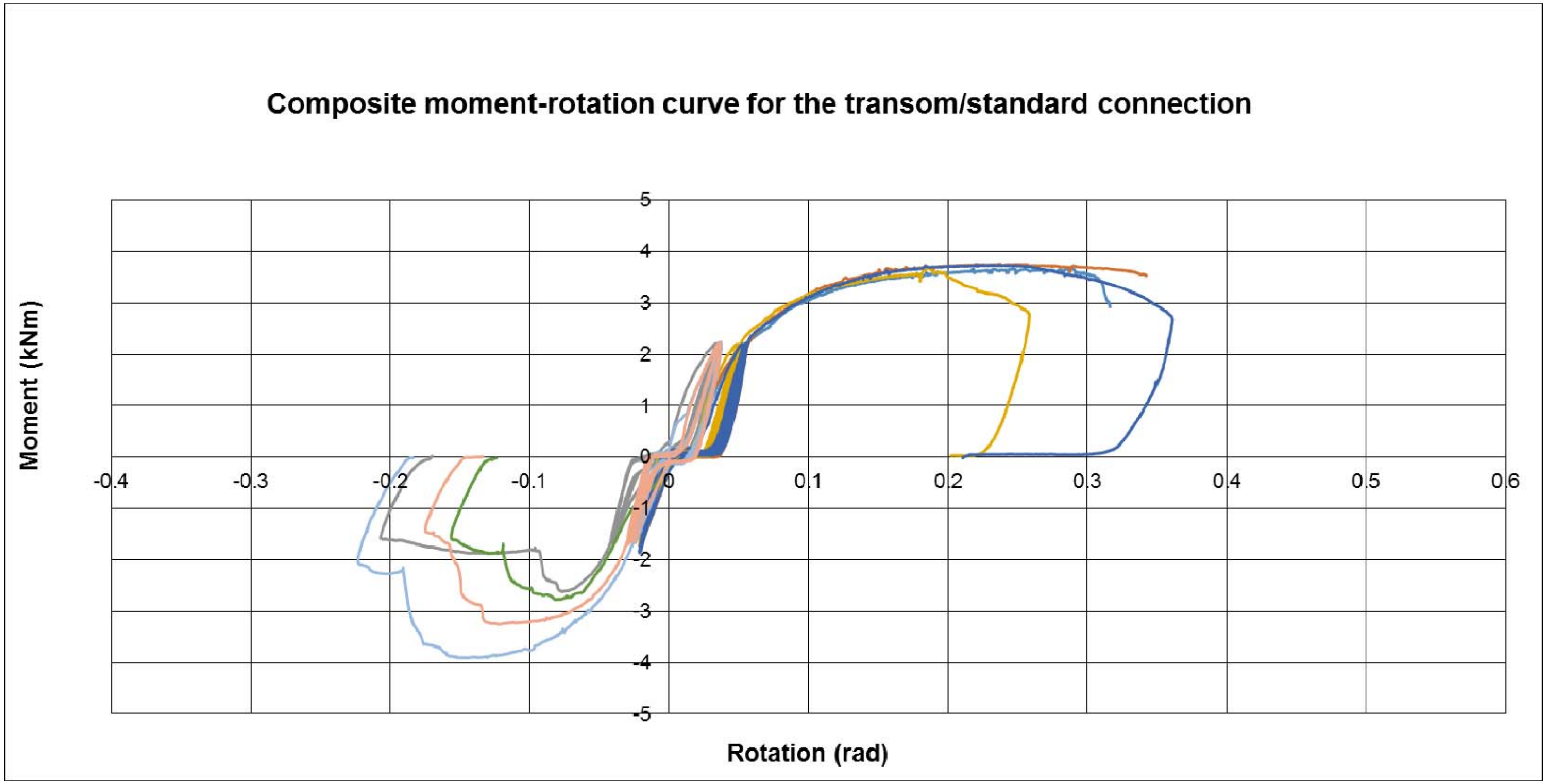


Figure 7: Moment-rotation curves for transom – standard tests

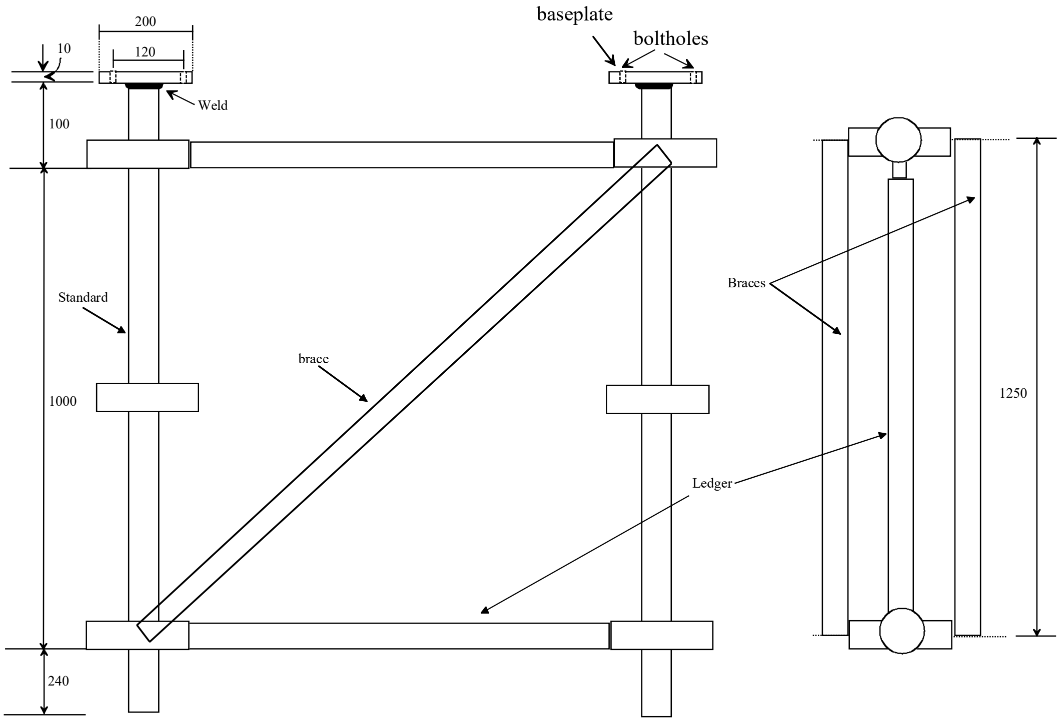


Figure 8: Schematic of brace test

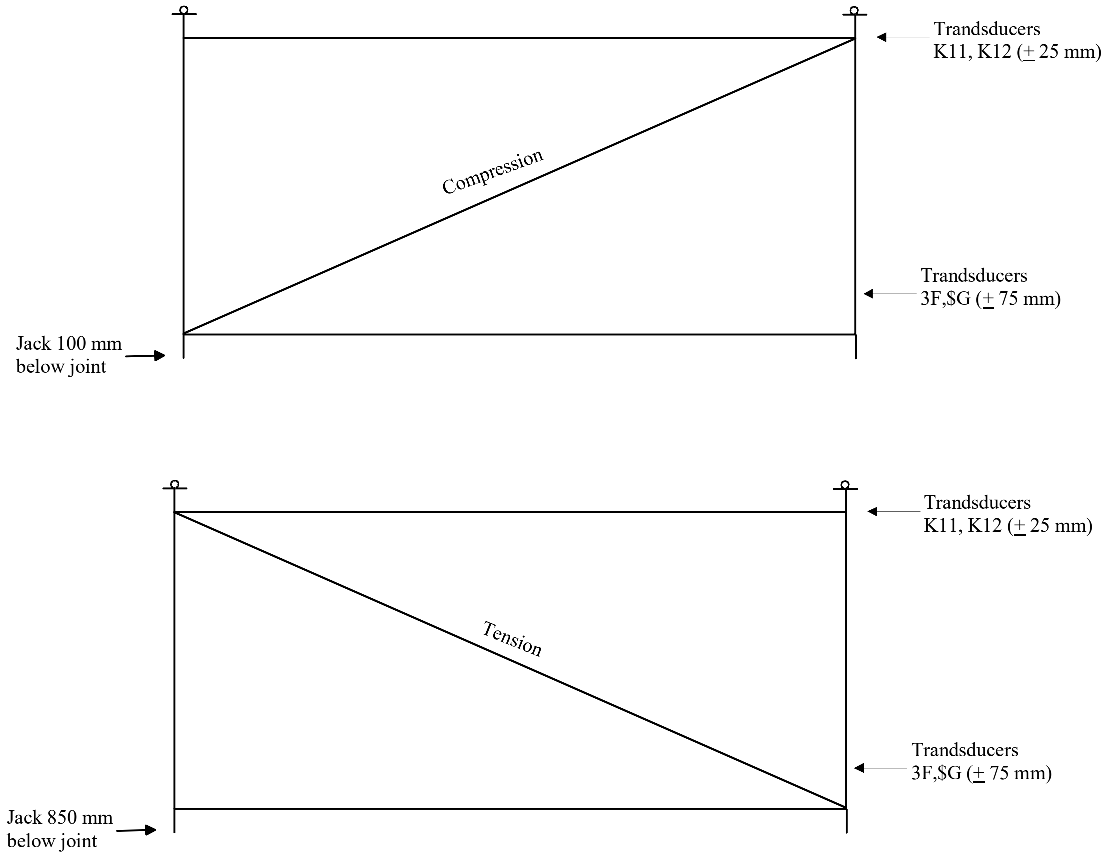


Figure 9: Load points and displacement transducer positions

Figure 10: General view of test arrangement (tension)

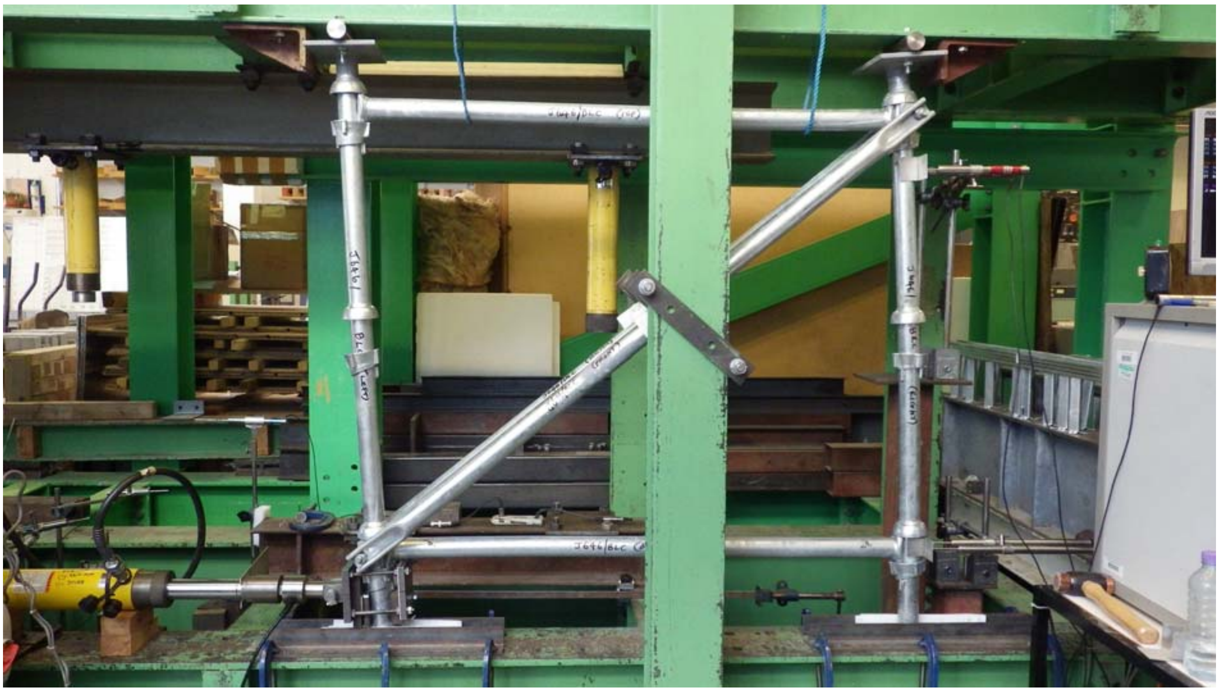


Figure 11: General view of test arrangement (compression)

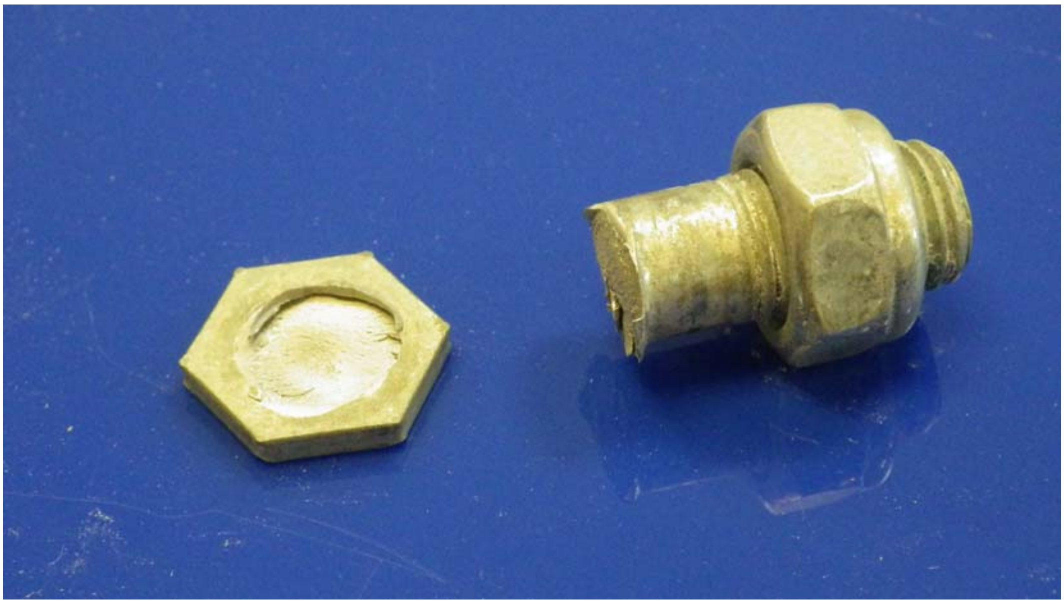


Figure 12: Bolt failure

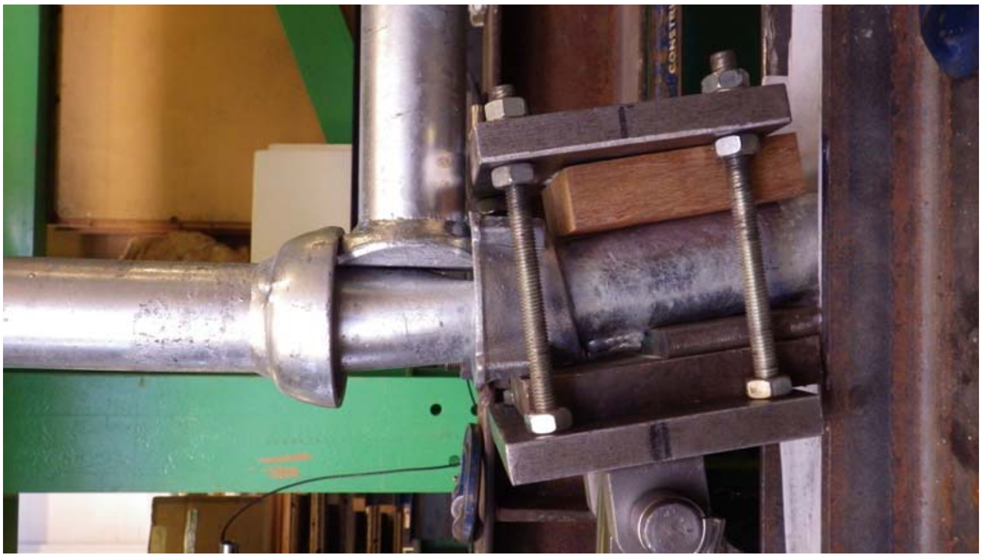


Figure 13: Standard distortion

Figure 14: Standard distortion at joint

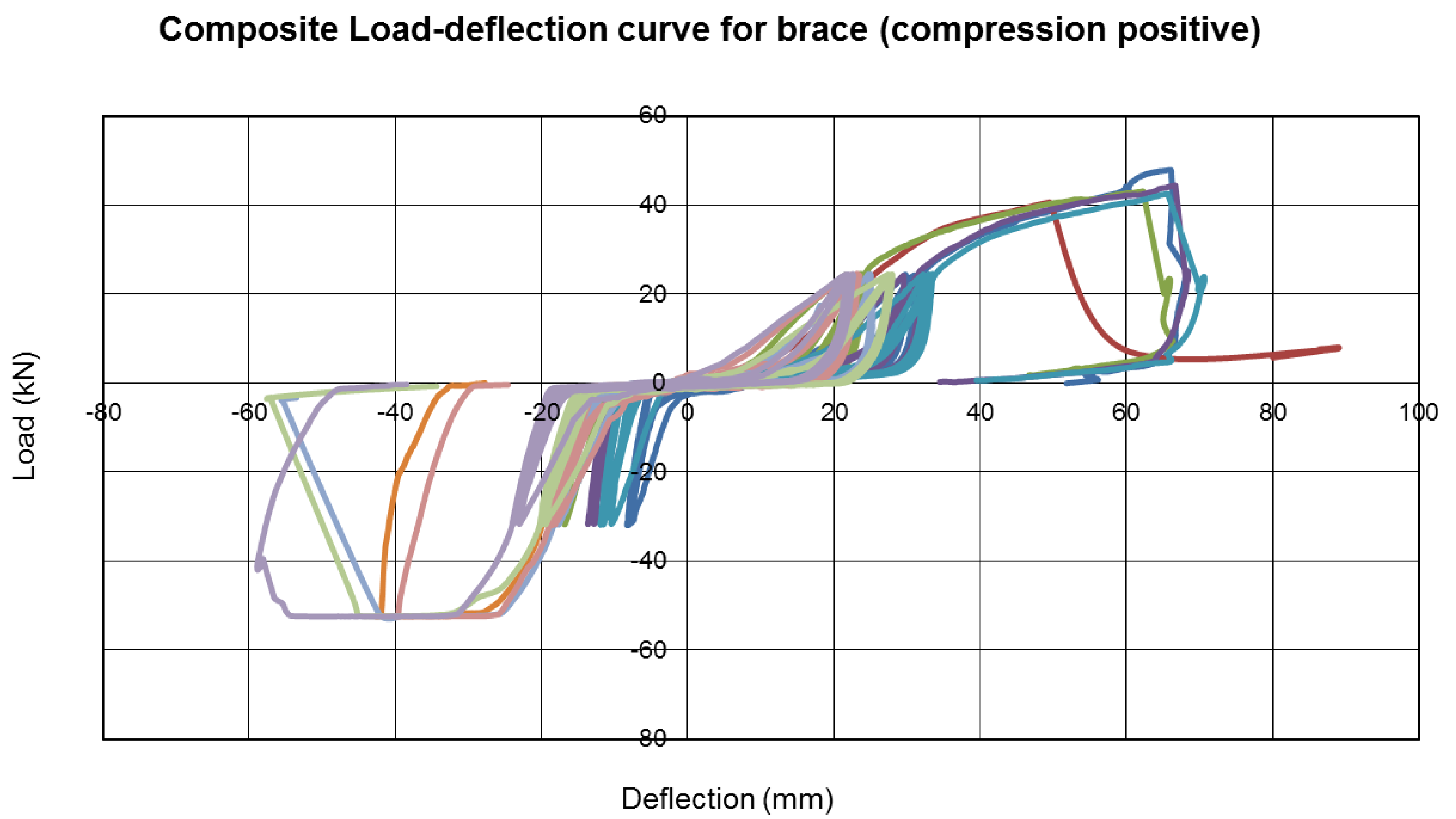


Figure 15: Load-deflection curves for all the brace cyclic tests

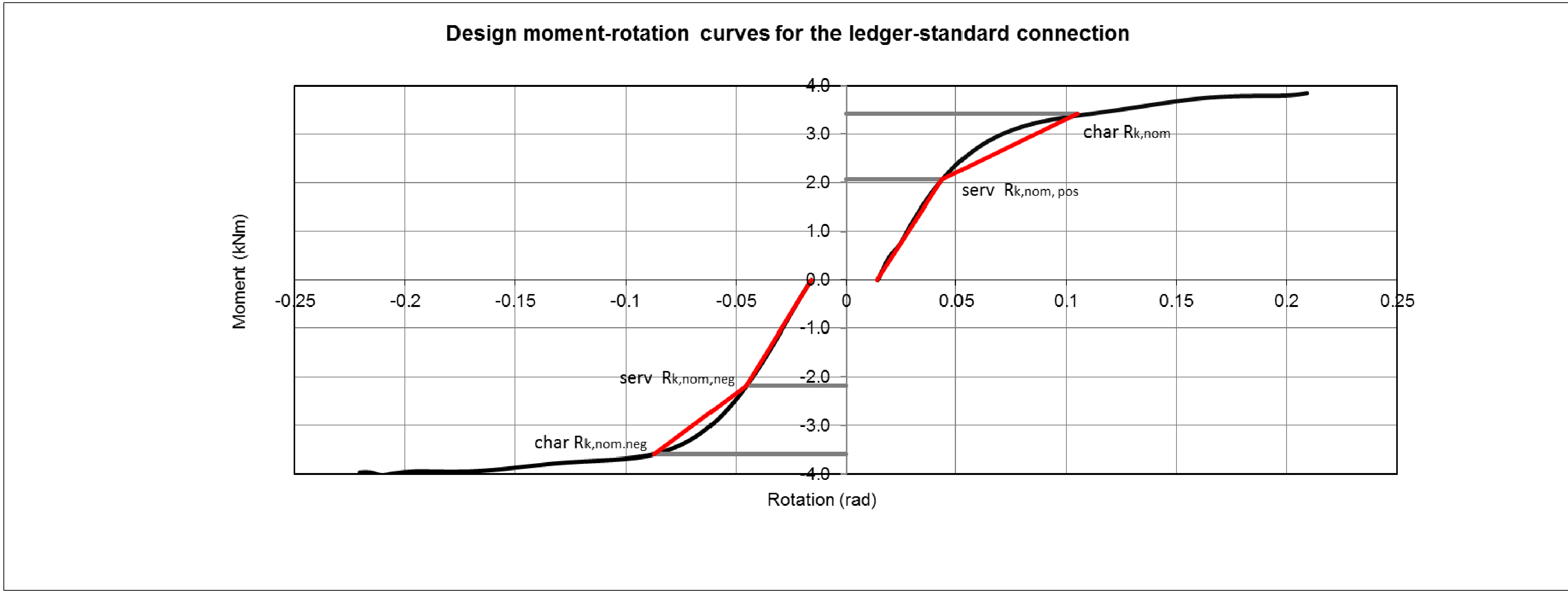


Figure 16: Design curves for the Ledger-standard connection

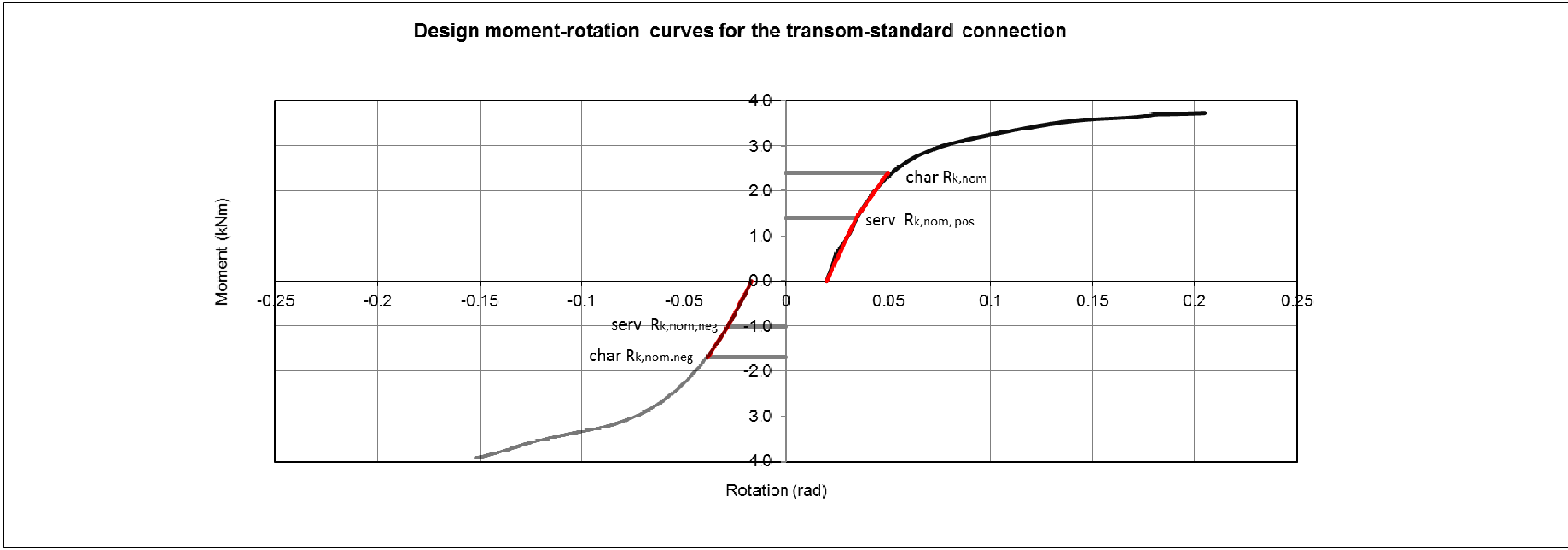


Figure 17: Design curves for the transom to standard connection

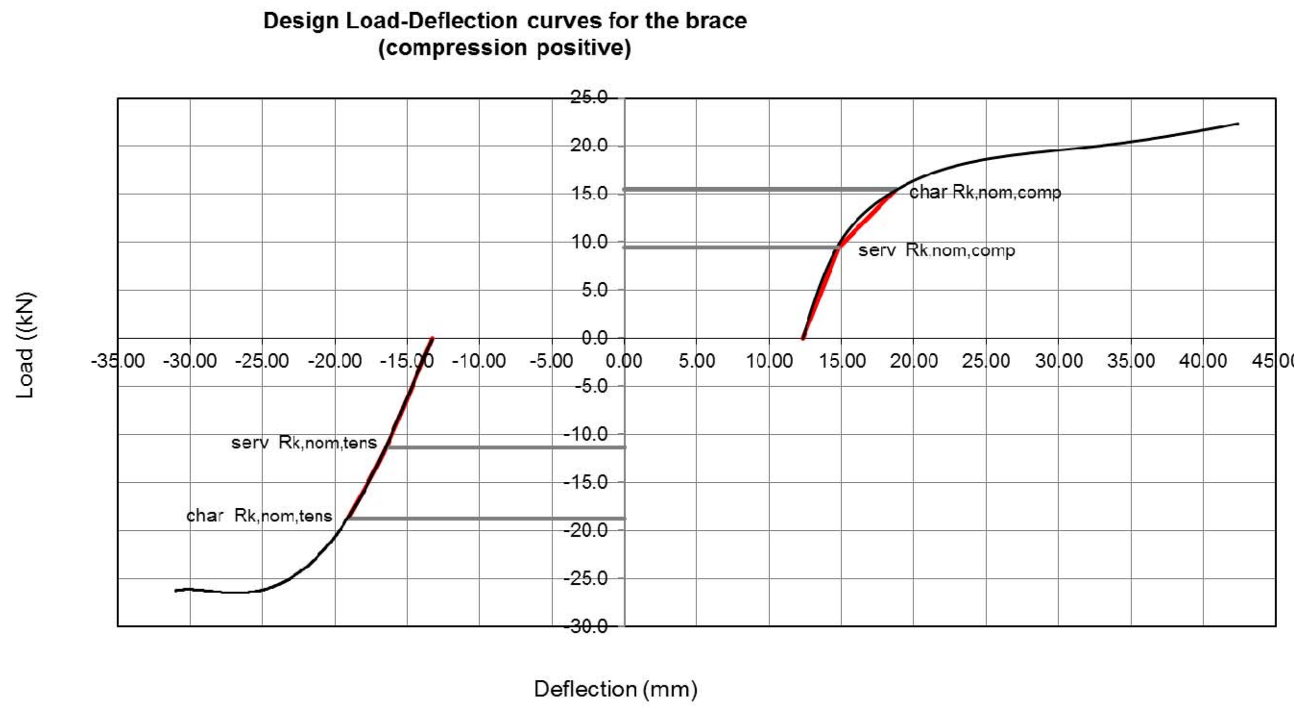


Figure 18: Design curves for the brace

Appendix 1: Test failure modes

Ledger tests

Tests undertaken at loading rate 0.1 mm/sec under displacement control, sample interval 1 second

Test Number	Test file	Cup elongation	Cup split	Cup rotation	Tongue bending	Tongue fracture	Standard distortion	Ledger distortion
3	J646LLFI	Y	Y	N	Y	N	N	N
5	J646LLFN	N	N	Y	N	Y	N	N
6	J646LCI1	N	Y	N	N	N	N	N
7	J646LCI2	N	Y	N	N	N	N	N
8	J646LCI3	N	Y	N	N	N	N	N
9	J646LCN1	N	Y	N	N	N	N	N
10	J646LCN2	Y	Y	N	N	N	N	N
11	J646LCN3	Y	Y	N	N	N	N	N

Note. Y = primary mode of failure

Transom tests
Tests undertaken at loading rate 0.1 mm/sec under displacement control, sample interval 1 second

Test Number	Test file	Cup elongation	Cup split	Weld fracture	Tongue bending	Tongue fracture	Cup ring distortion	Standard/ Transom distortion
14	J646TLFI	N	N	Y	N	N	N	N
16	J646TLFN	N	N	Y	Y	Y	Y	N
17	J646TCN1	N	N	Y	Y	Y	N	N
18	J646TCN2	N	N	Y	Y	Y	Y	N
19*	J646TCN3	N	N	N	N	Y	N	N
20	J646TCI1	Y	N	Y	Y	N	N	N
21	J646TCI2	Y	N	Y	N	N	N	N
22	J646TCI3	Y	N	Y	N	N	N	N

*Test 18 jumped from -3.9 to -4.4 KN

Note. Y = primary mode of failure

Bracing Tests
Loading rate 0.2 mm/sec, sample interval 0.5 seconds

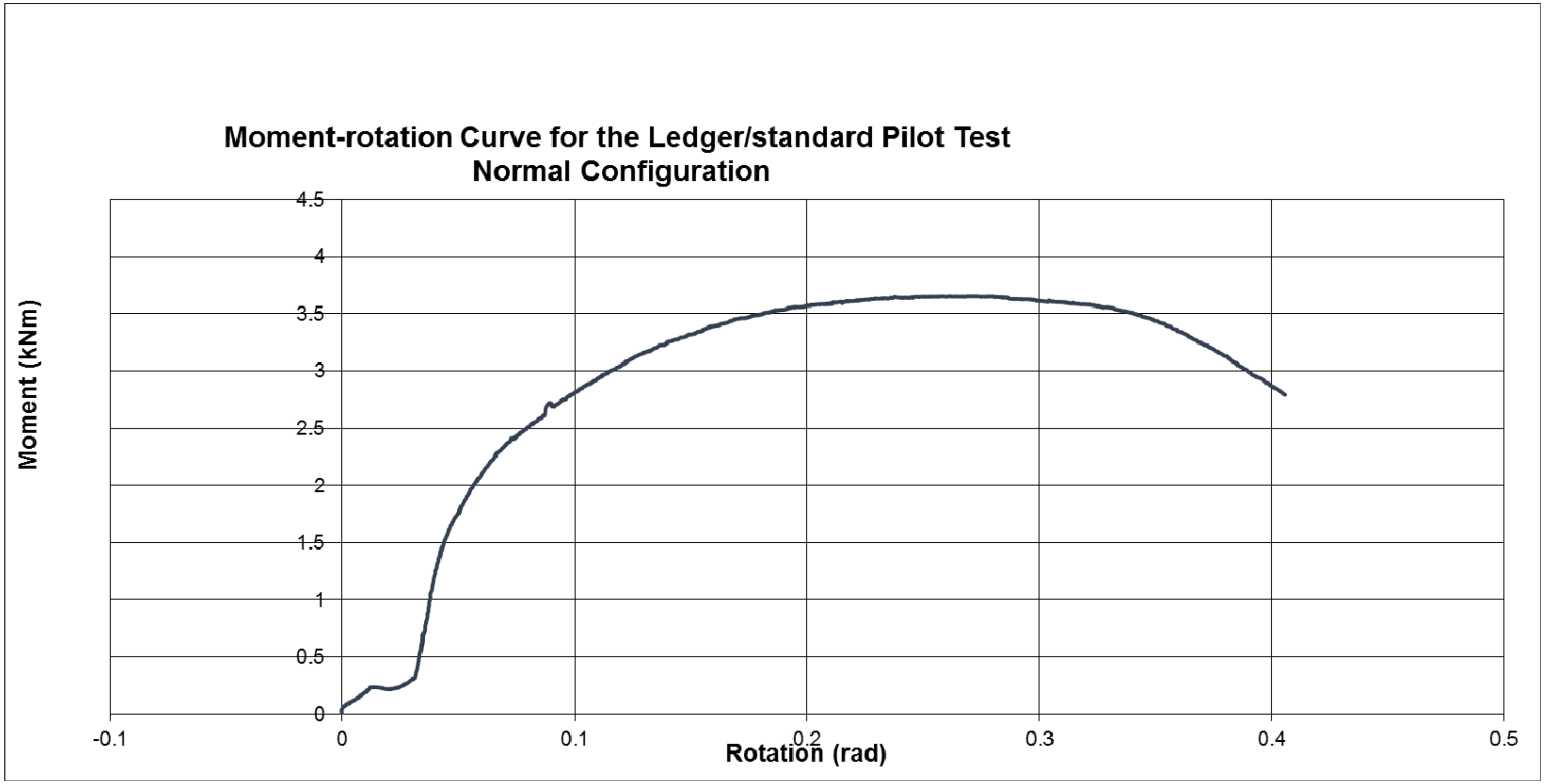
Test Number	Test file	Brace popped out	Weld failure	Bolt failure	Standard distortion	Standard buckled	Brace movement	Brace distortion
23	J646BLT	N	N	N	Y	Y	Y	N
24	J646BLC	N	N	Y	N	N	N	N
25	J646BCC1	N	N	Y	N	N	N	N
26	J646BCC2	N	N	Y	N	N	N	N
27	J646BCC3	N	N	Y	N	N	N	N
28	J646BCC4	N	N	N	N	N	N	N
29*	J646BCT1	Y	N	N	Y	N	N	N
30*	J646BCT2	Y	Y	N	Y	N	N	N
31*	J624BCT3	Y	N	N	N	N	Y	N
32*	J624BCT4	Y	N	N	N	N	Y	N

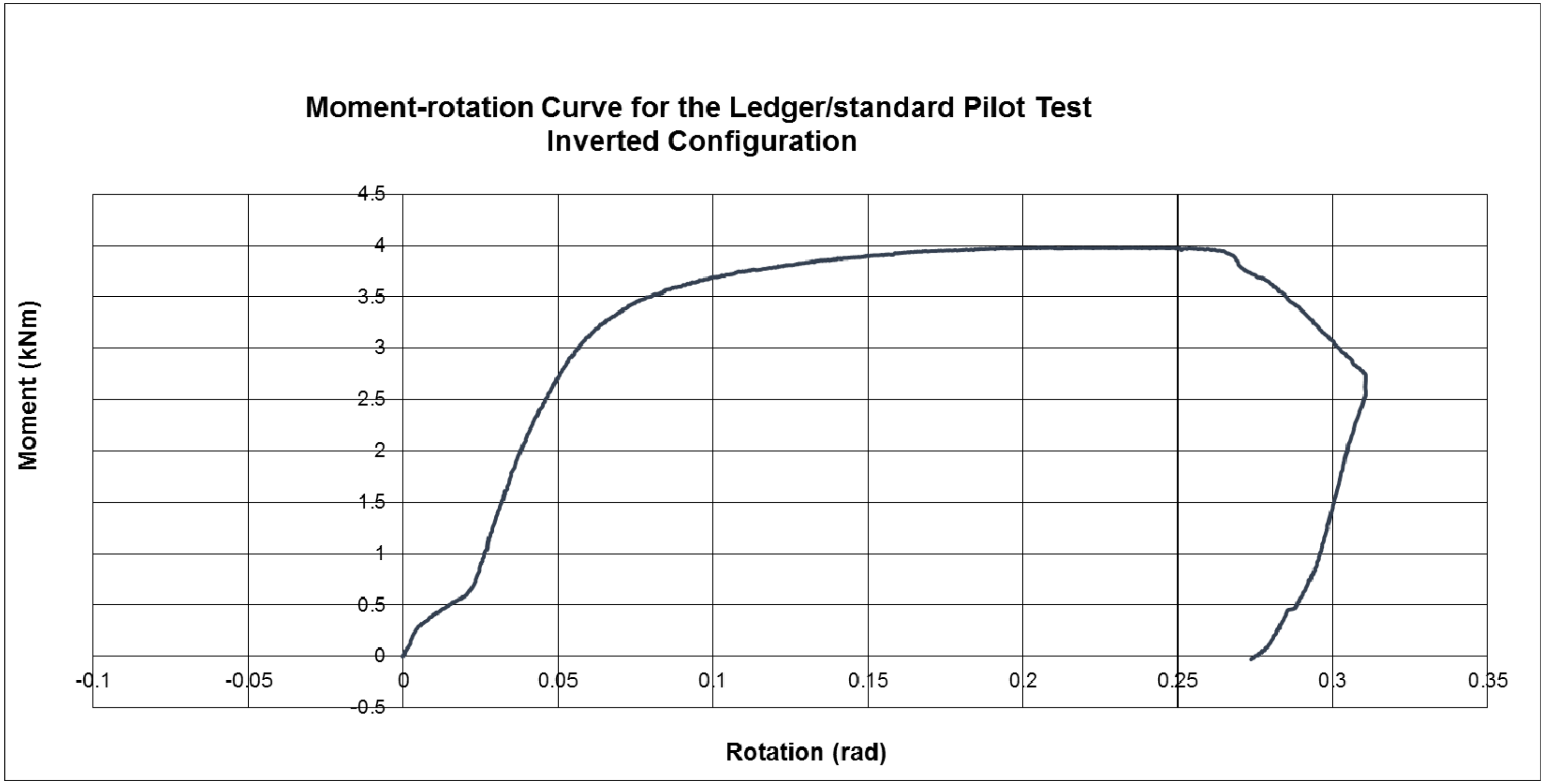
*Loading rate 0.4 mm/sec

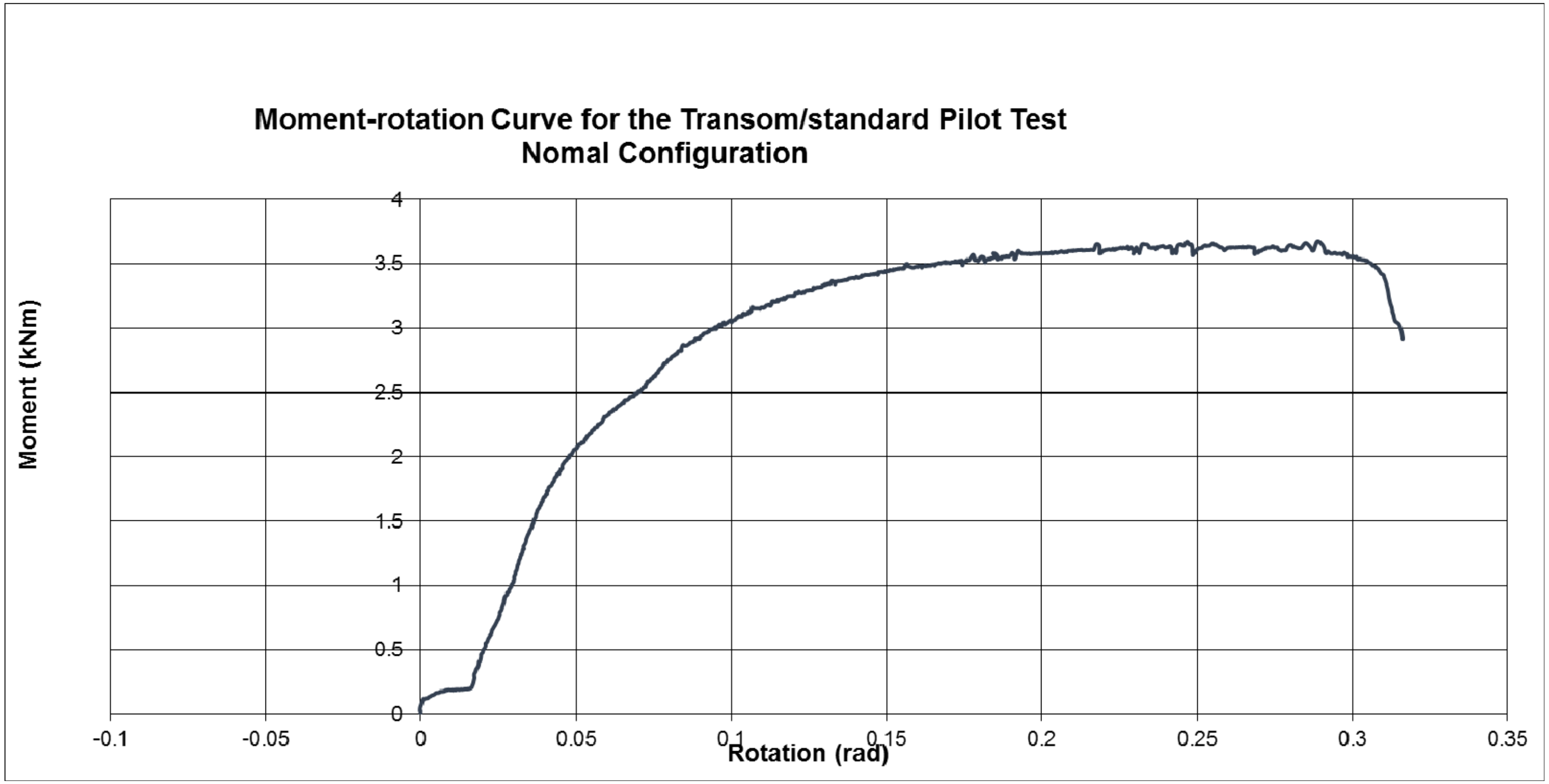
Note. Y = primary mode of failure

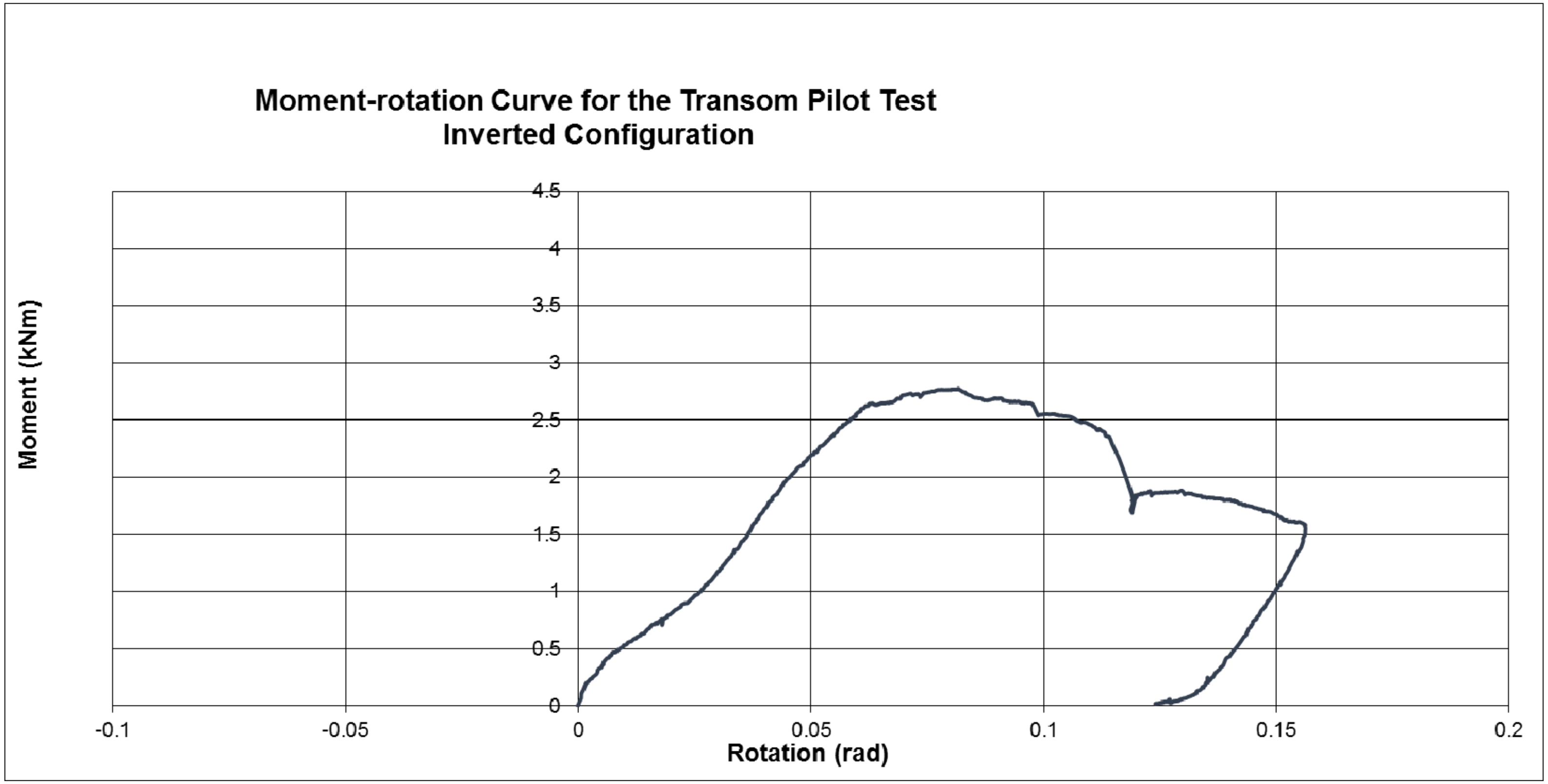
Appendix 2: Moment-rotation curves

(a) Initial tests to failure for ledger/transom-standard connections

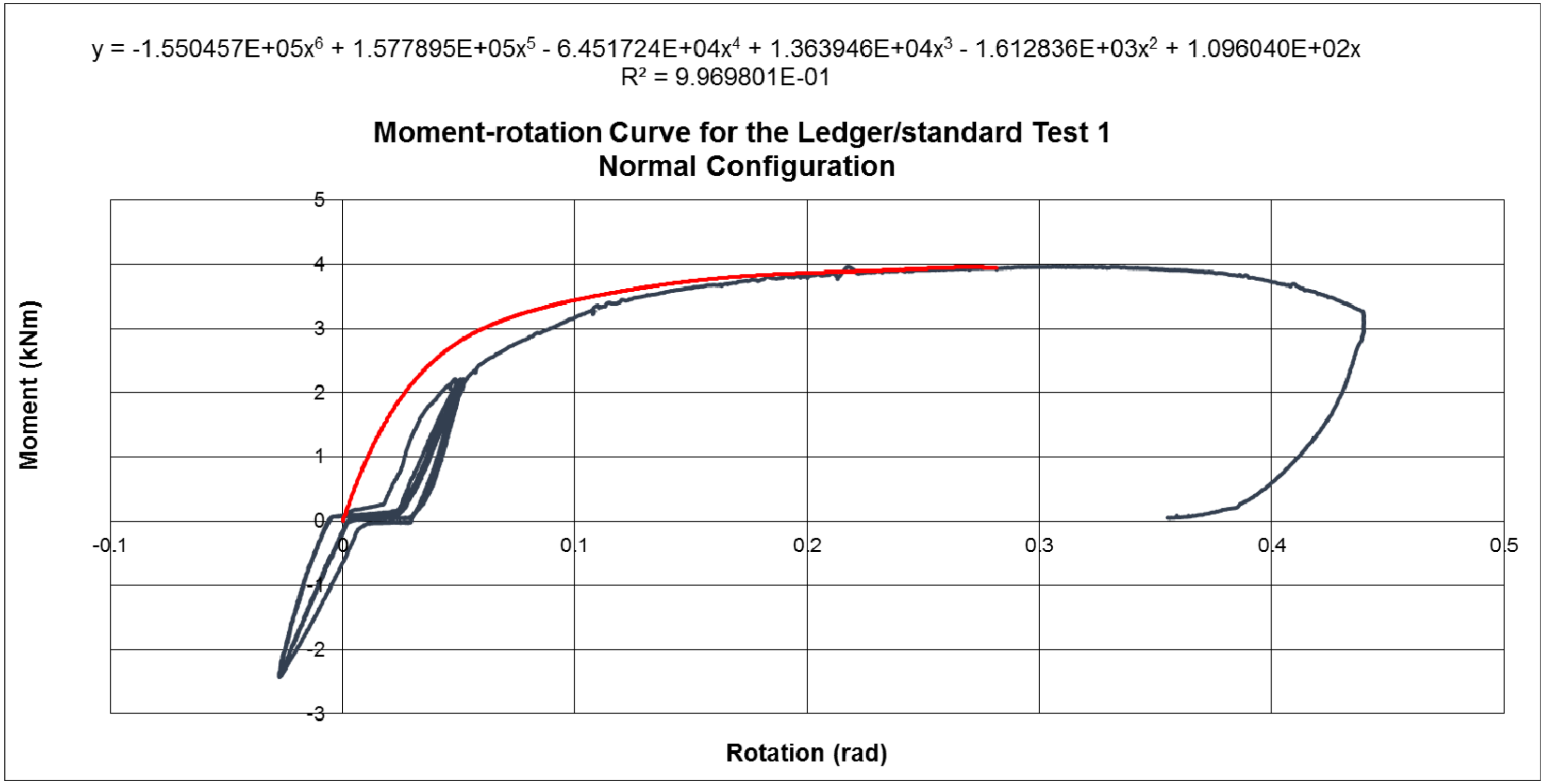


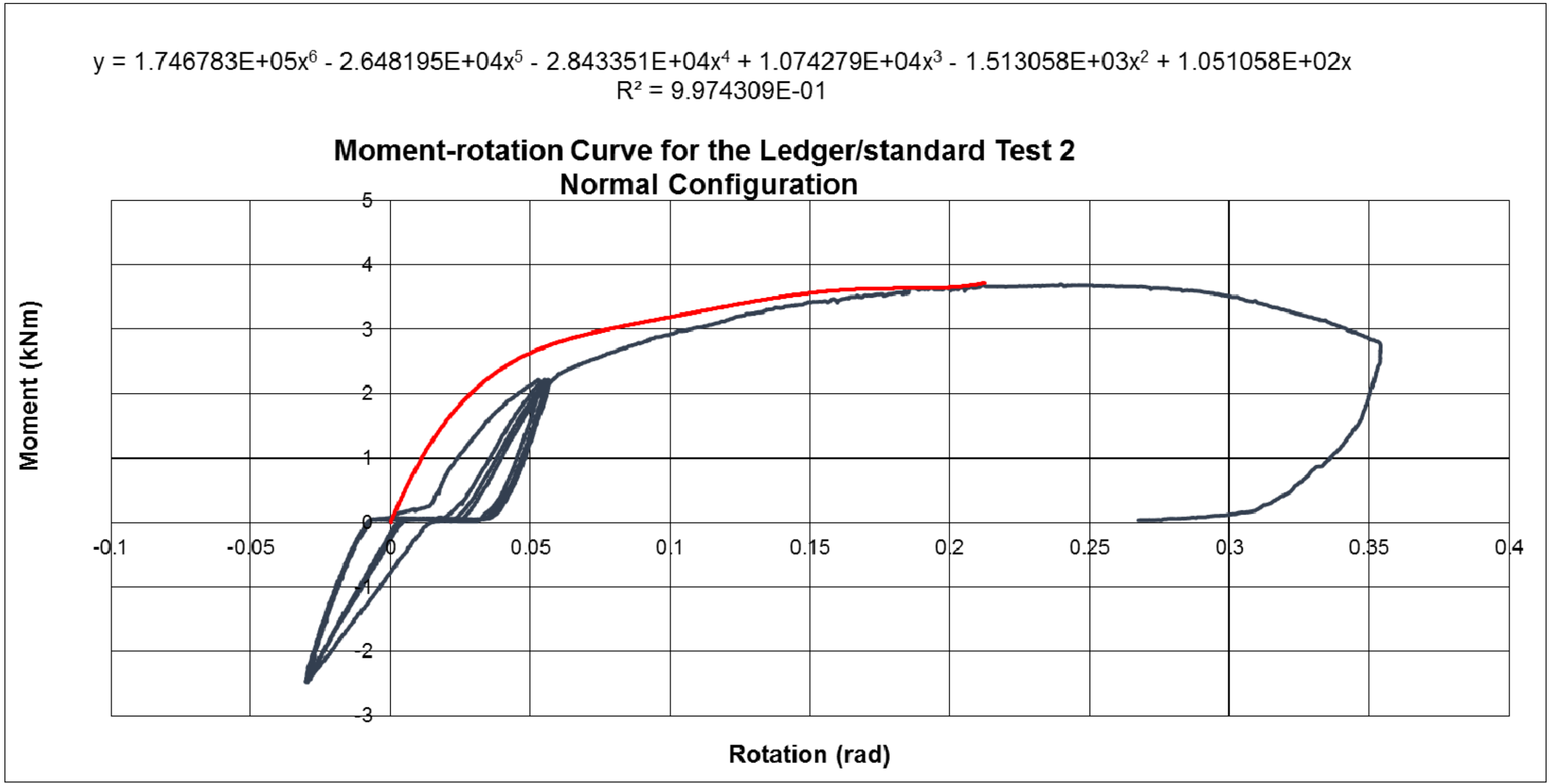

Moment-rotation Curve for the Ledger/standard Pilot Test
Inverted Configuration
Moment (kNm)
Rotation (rad)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35


Moment-rotation Curve for the Transom/standard Pilot Test
Nomal Configuration
Moment (kNm)
Rotation (rad)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

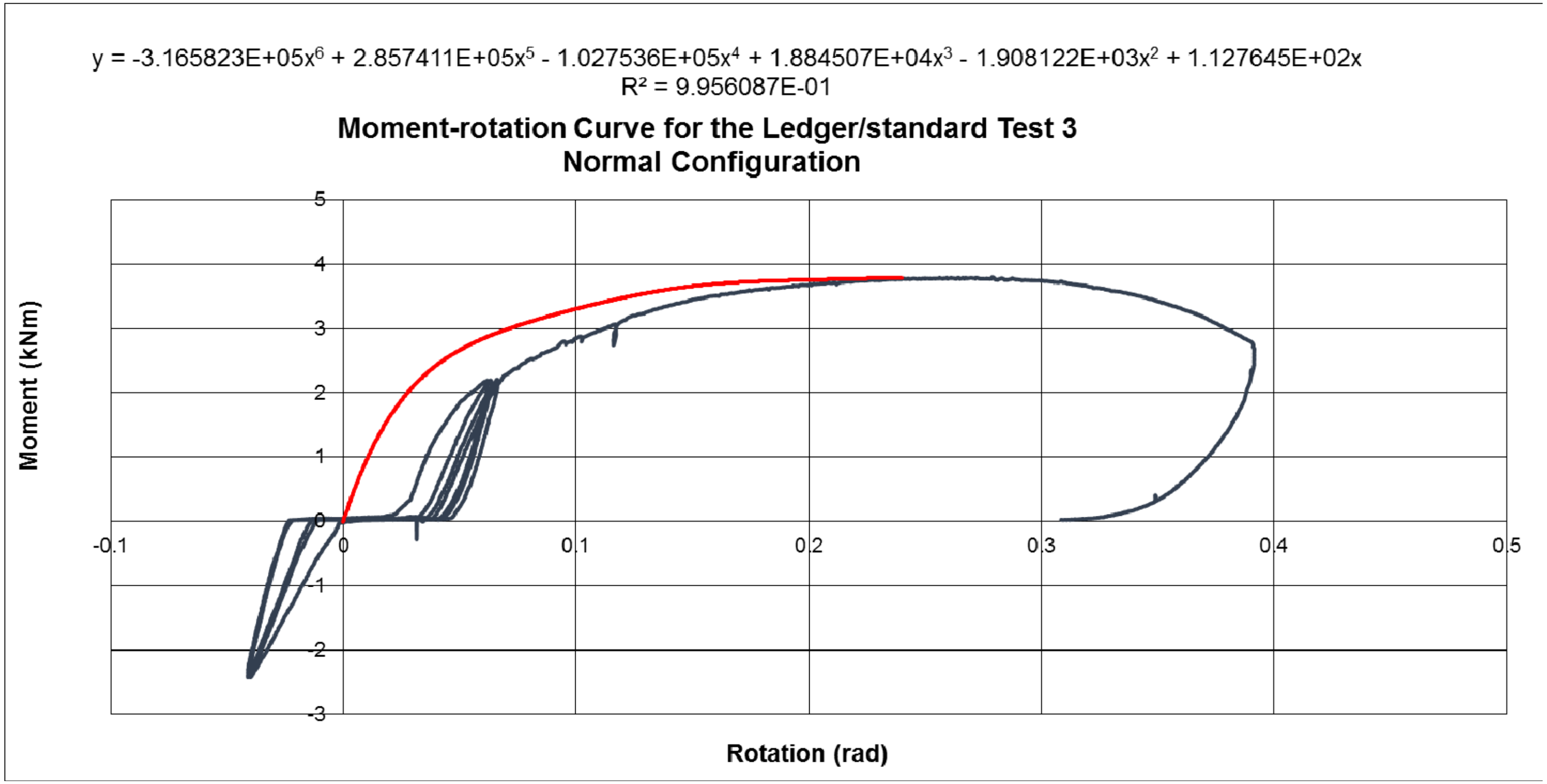

Moment-rotation Curve for the Transom Pilot Test
Inverted Configuration
Moment (kNm)
Rotation (rad)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.1
-0.05
0
0.05
0.1
0.15
0.2

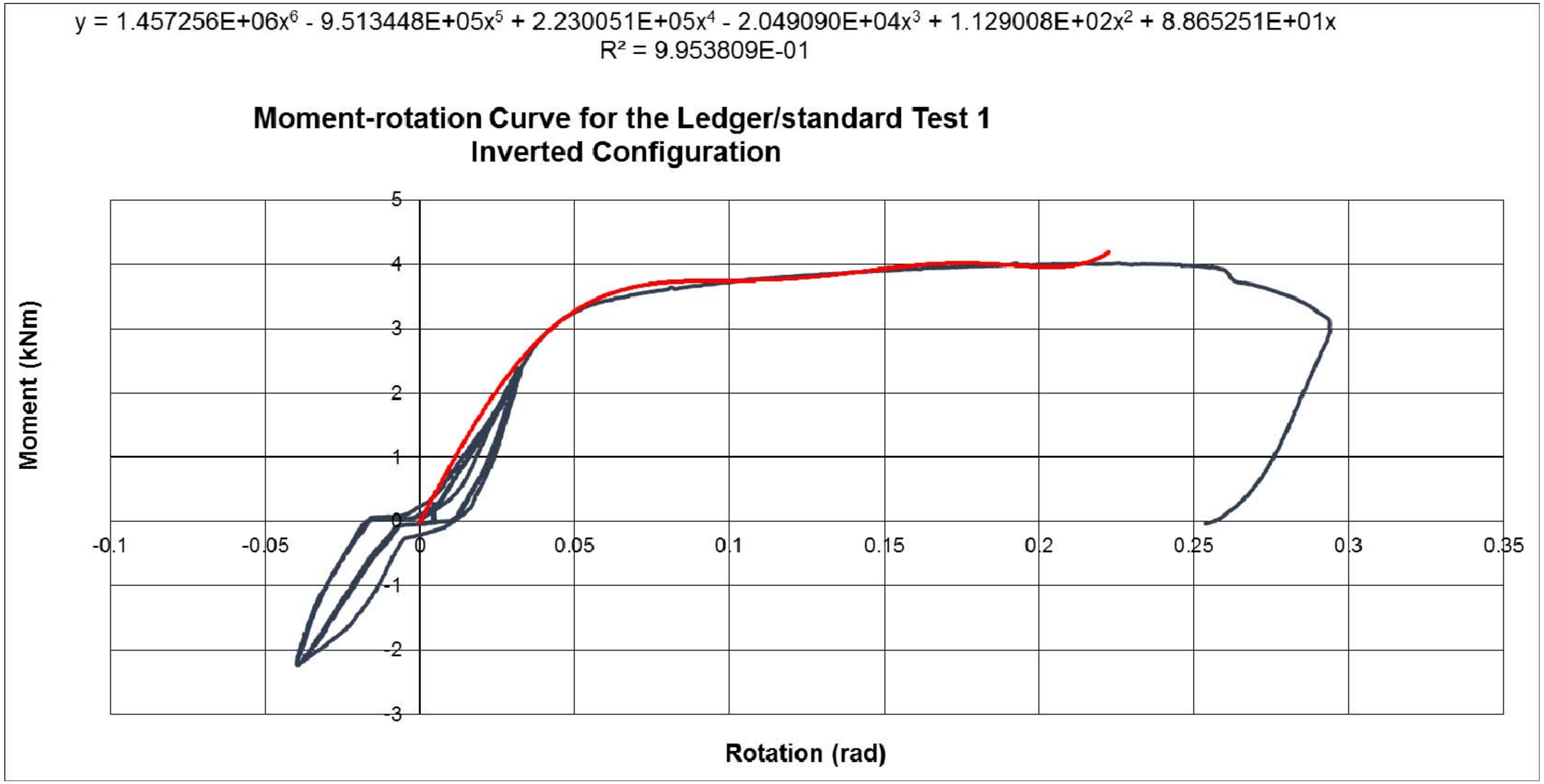
(b) Cyclic tests on ledger-standard connections

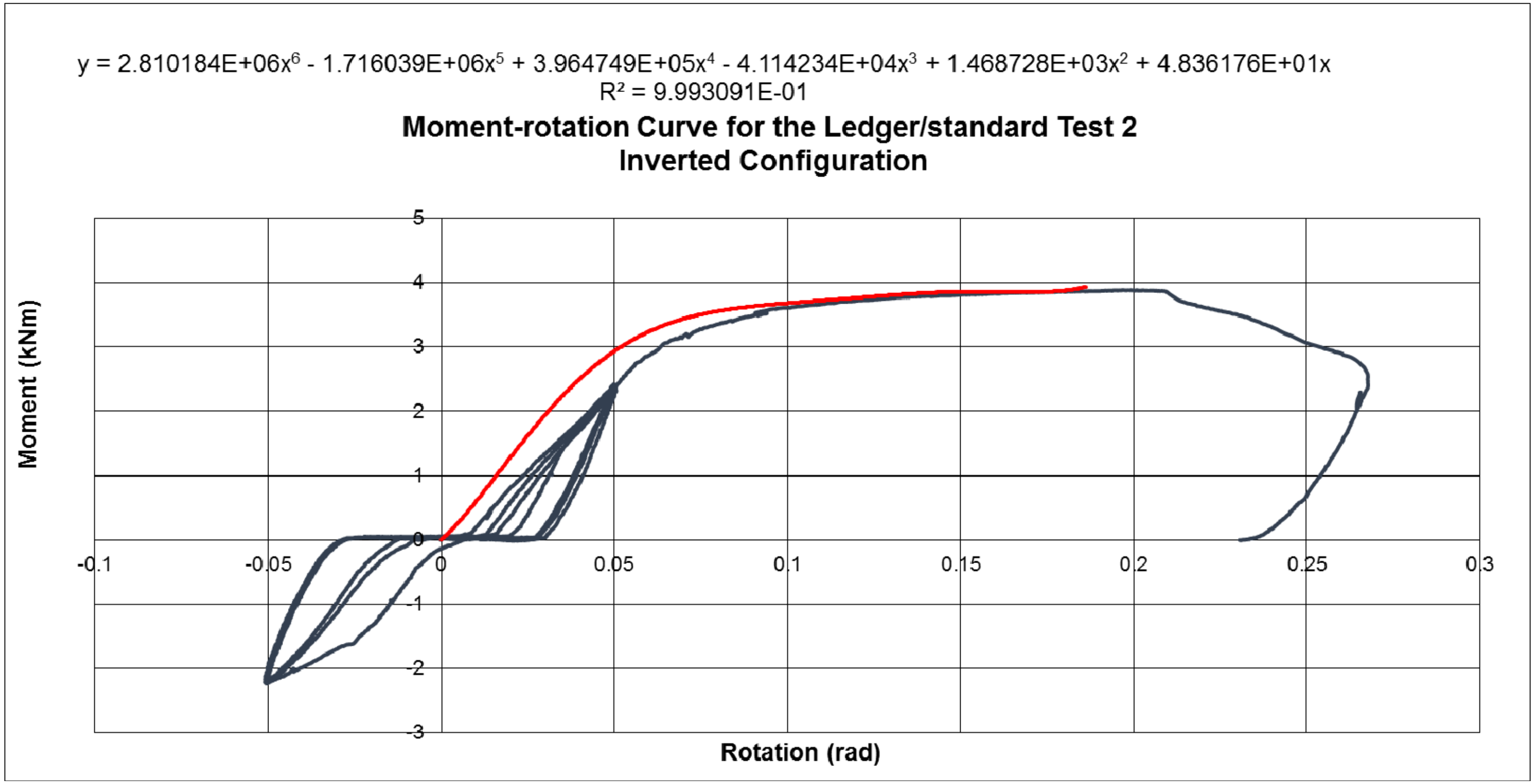




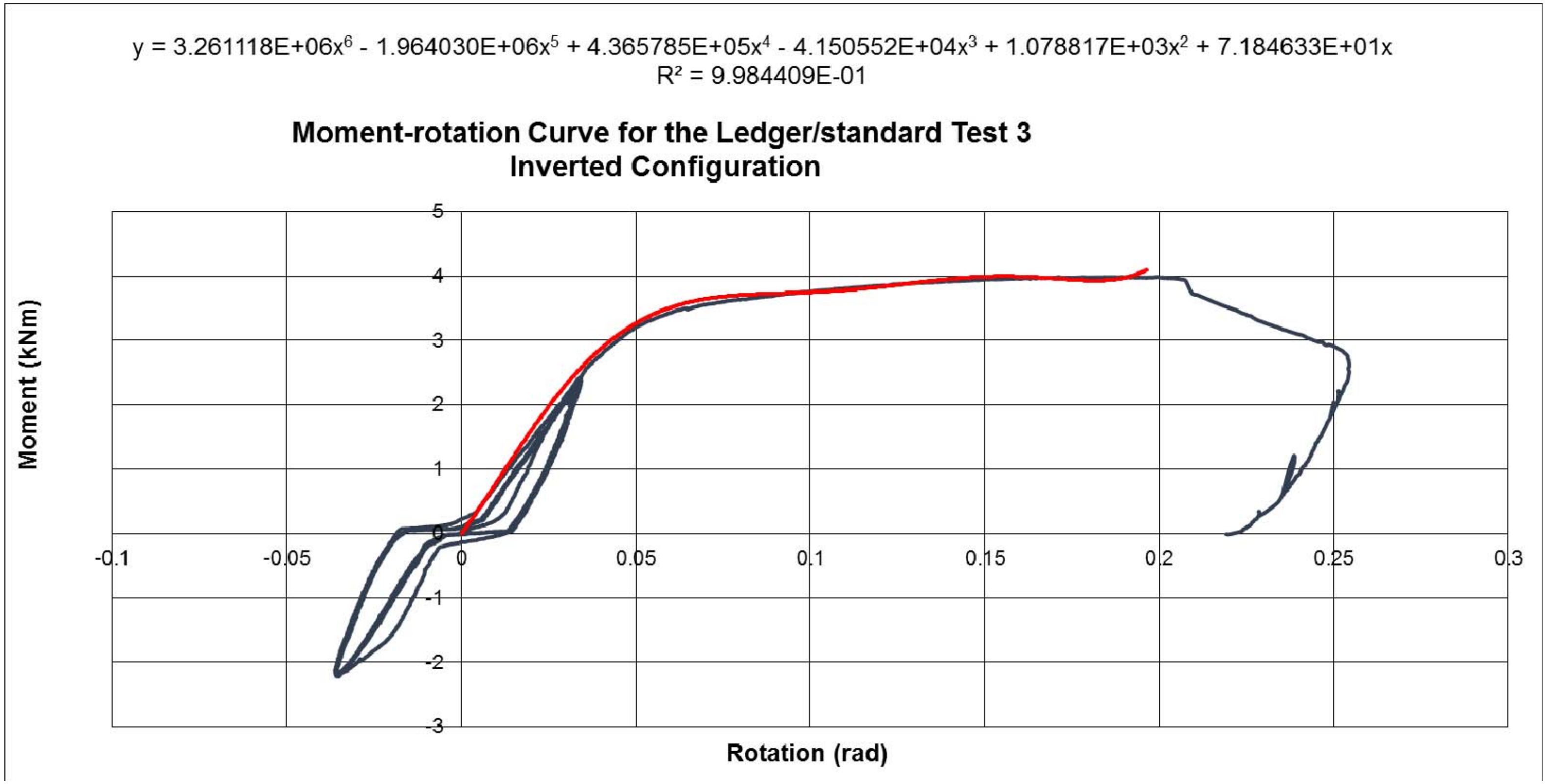
y = 1.746783E+05x6 - 2.648195E+04x5 - 2.843351E+04x4 + 1.074279E+04x3 - 1.513058E+03x2 + 1.051058E+02x
R² = 9.974309E-01
Moment-rotation Curve for the Ledger/standard Test 2
Normal Configuration
Moment (kNm)
Rotation (rad)
5
4
3
2
1
0
-1
-2
-3
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4


y = -3.165823E+05x6 + 2.857411E+05x5 - 1.027536E+05x4 + 1.884507E+04x3 - 1.908122E+03x2 + 1.127645E+02x
R² = 9.956087E-01
Moment-rotation Curve for the Ledger/standard Test 3
Normal Configuration
Moment (kNm)
Rotation (rad)
5
4
3
2
1
0
-1
-2
-3
-0.1
0
0.1
0.2
0.3
0.4
0.5

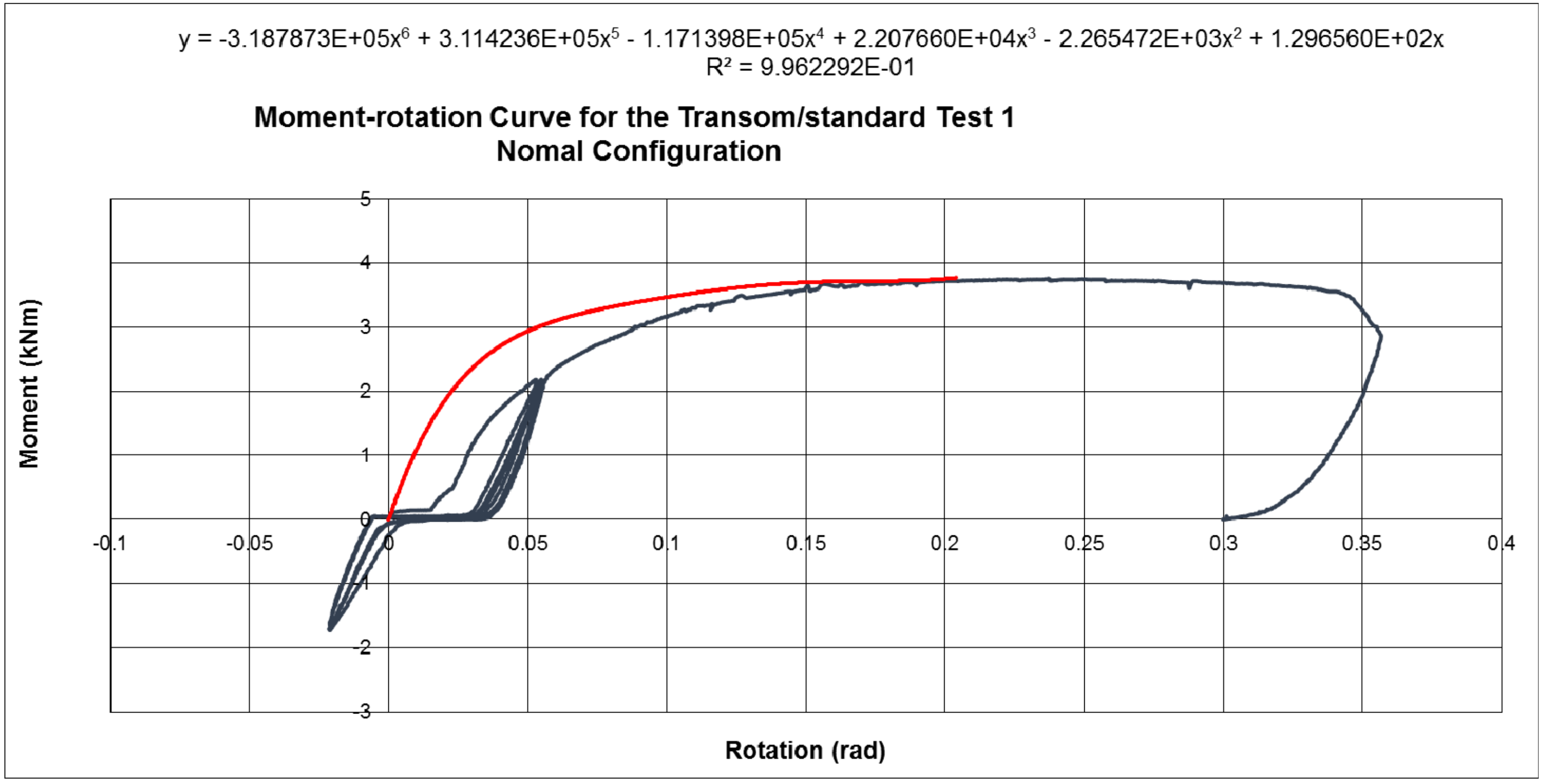

y = 1.457256E+06x6 - 9.513448E+05x5 + 2.230051E+05x4 - 2.049090E+04x3 + 1.129008E+02x2 + 8.865251E+01x
R² = 9.953809E-01
Moment-rotation Curve for the Ledger/standard Test 1
Inverted Configuration
Moment (kNm)
Rotation (rad)
5
4
3
2
1
0
-1
-2
-3
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

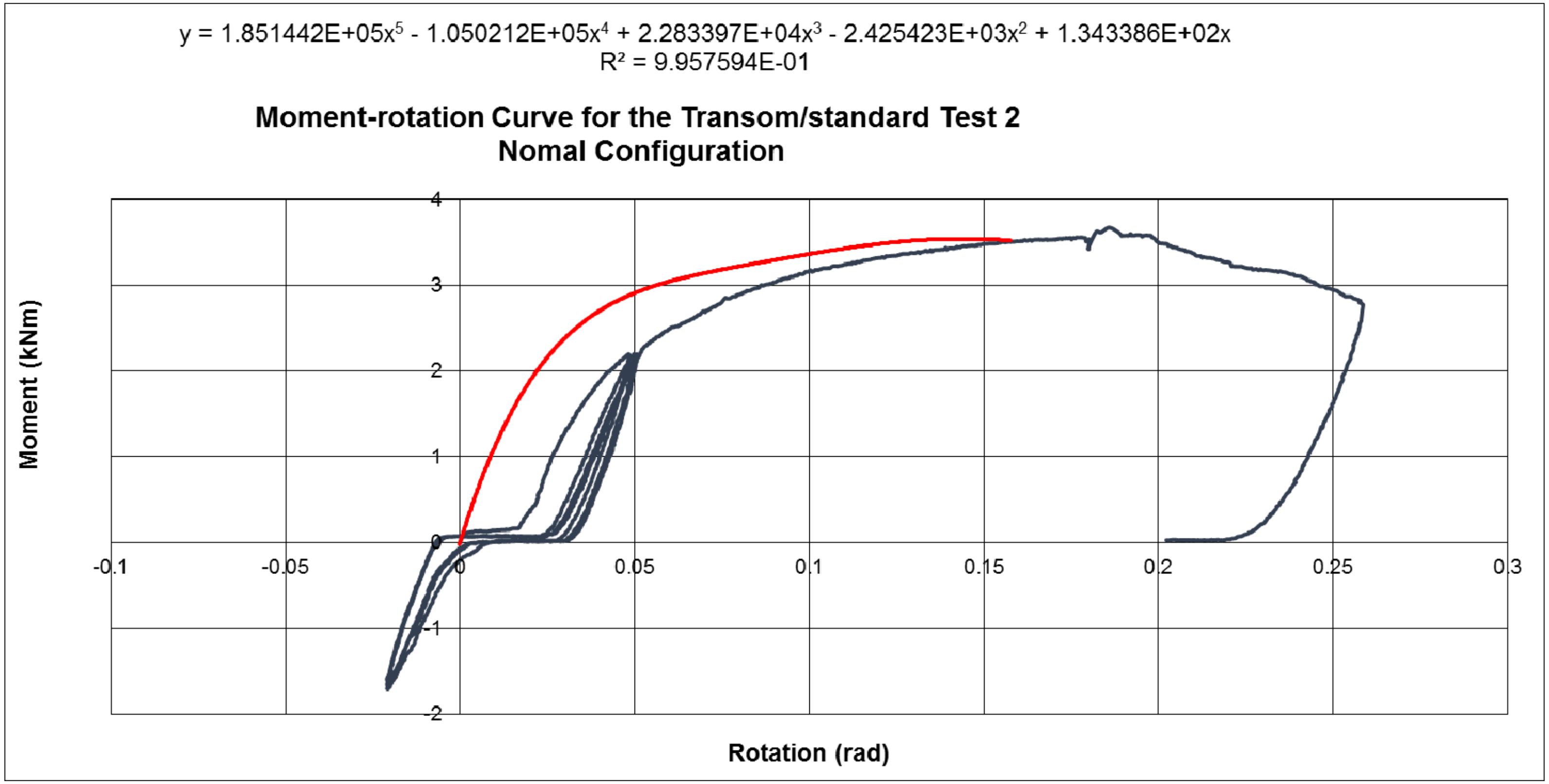


y = 2.810184E+06x6 - 1.716039E+06x5 + 3.964749E+05x4 - 4.114234E+04x3 + 1.468728E+03x2 + 4.836176E+01x
R² = 9.993091E-01
Moment-rotation Curve for the Ledger/standard Test 2
Inverted Configuration
Moment (kNm)
Rotation (rad)
5
4
3
2
1
0
-1
-2
-3
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3

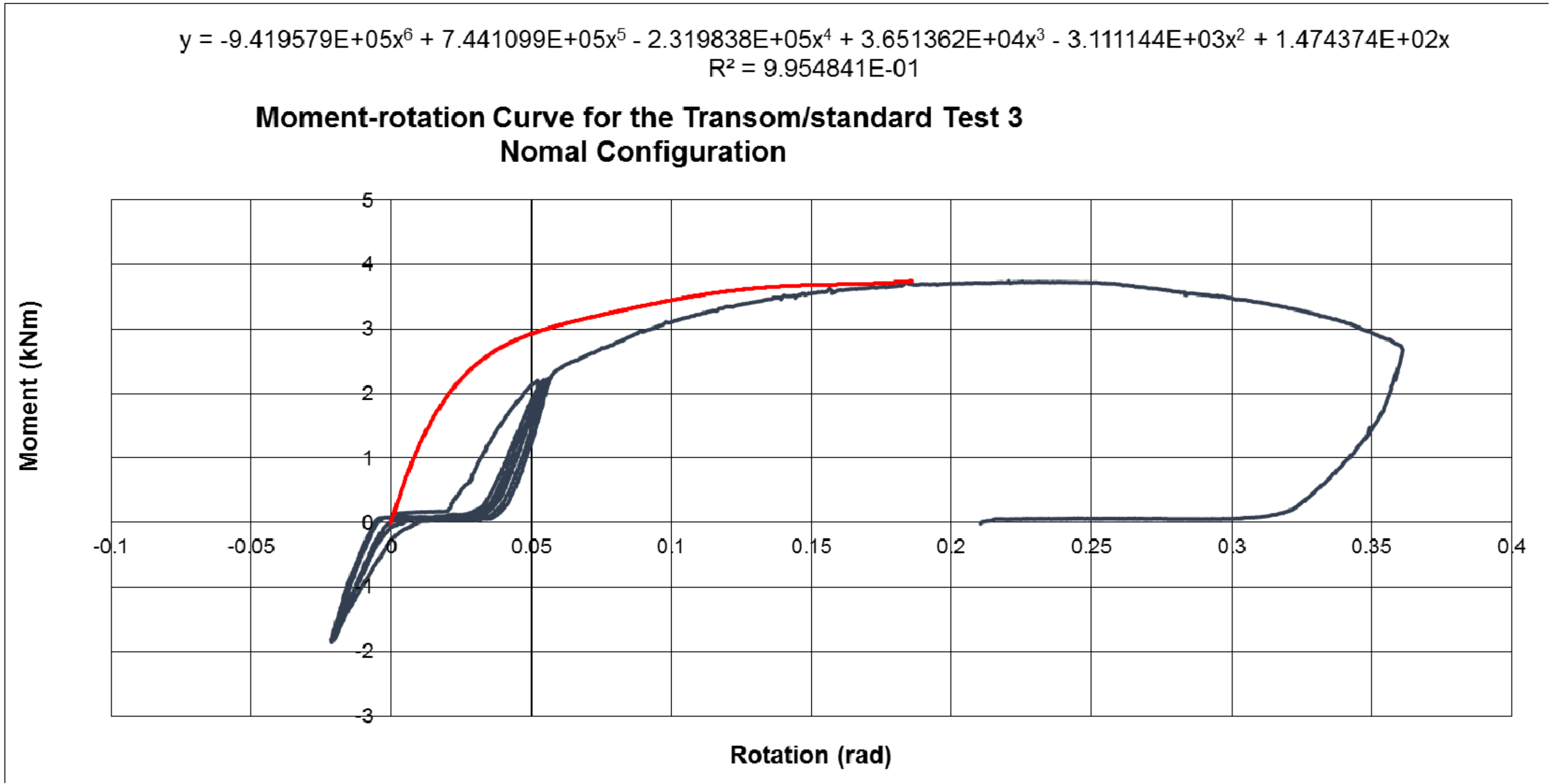

y = 3.261118E+06x6 - 1.964030E+06x5 + 4.365785E+05x4 - 4.150552E+04x3 + 1.078817E+03x2 + 7.184633E+01x
R² = 9.984409E-01
Moment-rotation Curve for the Ledger/standard Test 3
Inverted Configuration
Moment (kNm)
Rotation (rad)
5
4
3
2
1
0
-1
-2
-3
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3

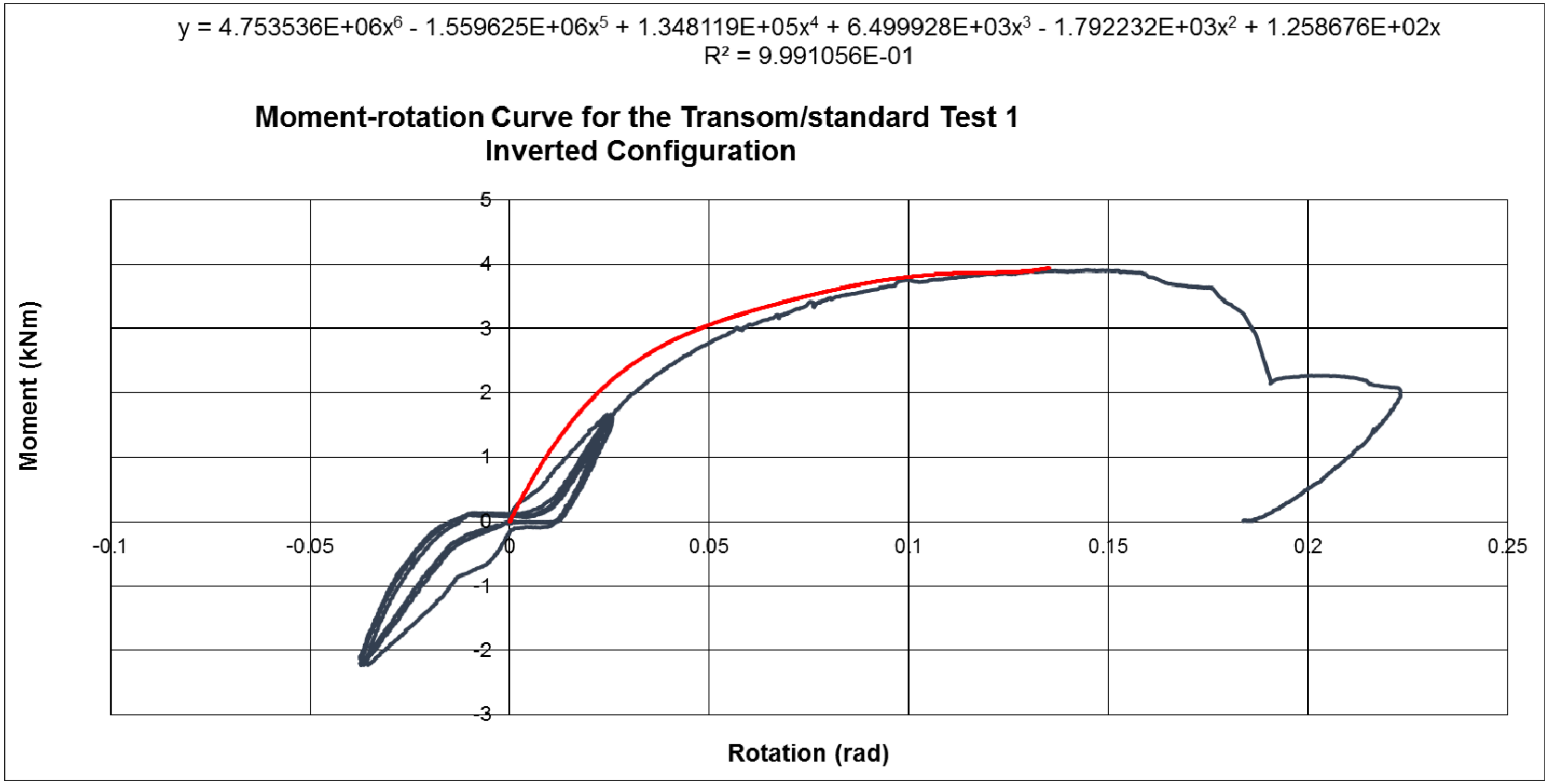
(c) Cyclic tests on transom-standard connections

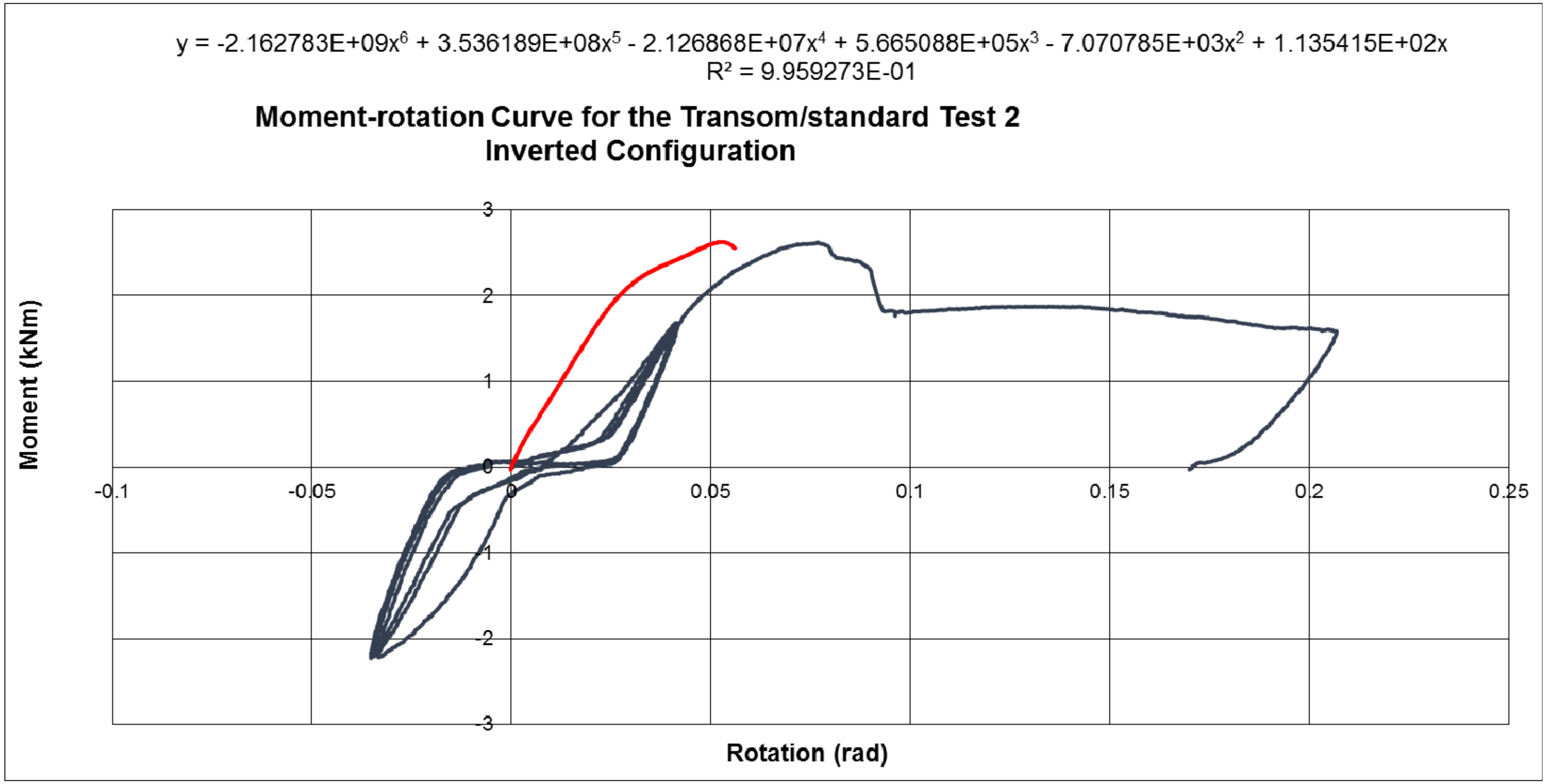


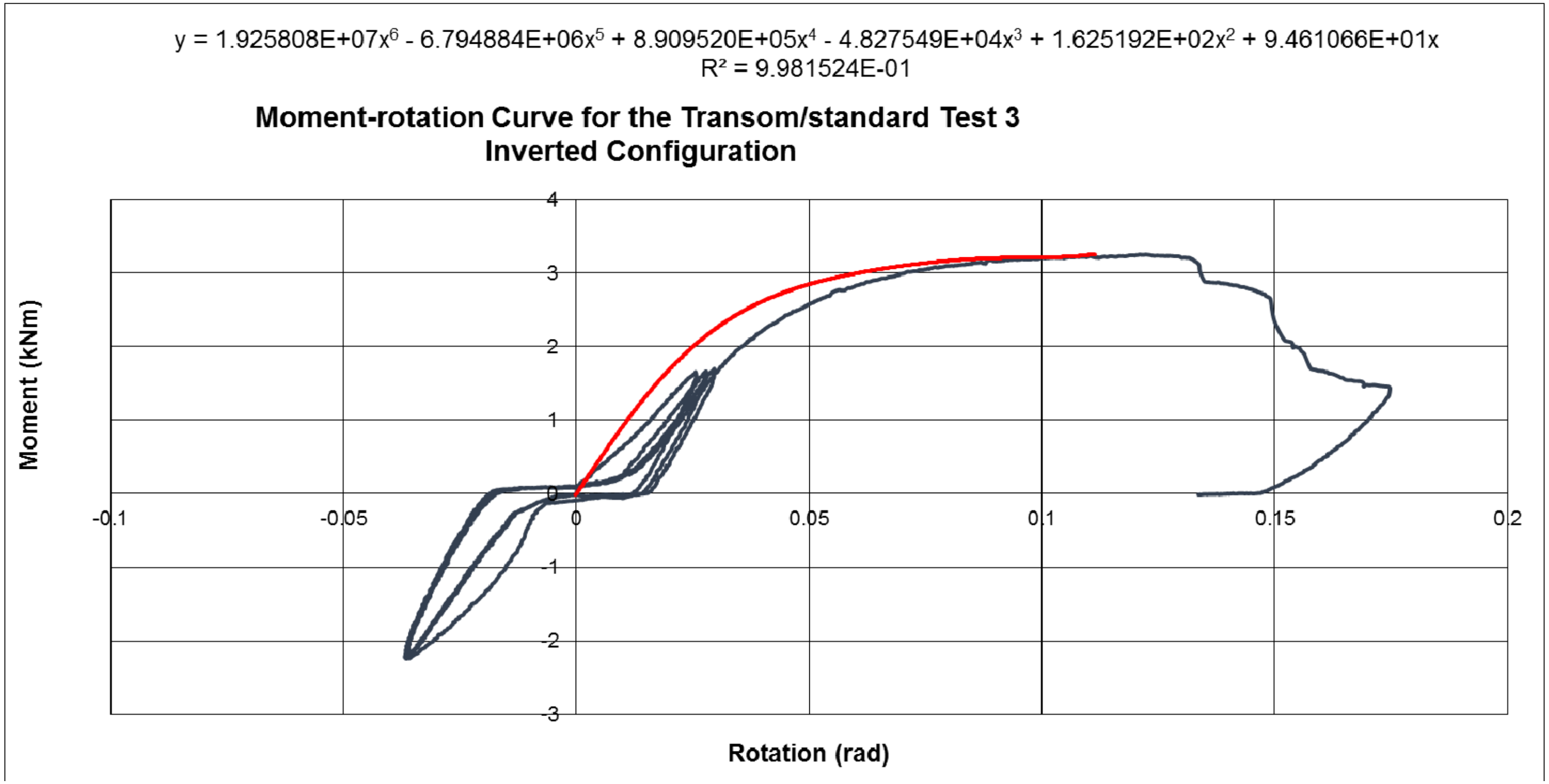


y = 1.851442E+05x5 - 1.050212E+05x4 + 2.283397E+04x3 - 2.425423E+03x2 + 1.343386E+02x
R² = 9.957594E-01
Moment-rotation Curve for the Transom/standard Test 2
Nomal Configuration
Moment (kNm)
Rotation (rad)
4
3
2
1
0
-1
-2
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3


y = -9.419579E+05x6 + 7.441099E+05x5 - 2.319838E+05x4 + 3.651362E+04x3 - 3.111144E+03x2 + 1.474374E+02x
R² = 9.954841E-01
Moment-rotation Curve for the Transom/standard Test 3
Nomal Configuration
Moment (kNm)
Rotation (rad)
5
4
3
2
1
0
-1
-2
-3
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4


y = 4.753536E+06x⁶ - 1.559625E+06x⁵ + 1.348119E+05x⁴ + 6.499928E+03x³ - 1.792232E+03x² + 1.258676E+02x
R² = 9.991056E-01
Moment-rotation Curve for the Transom/standard Test 1
Inverted Configuration
Moment (kNm)
Rotation (rad)
5
4
3
2
1
0
-1
-2
-3
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25

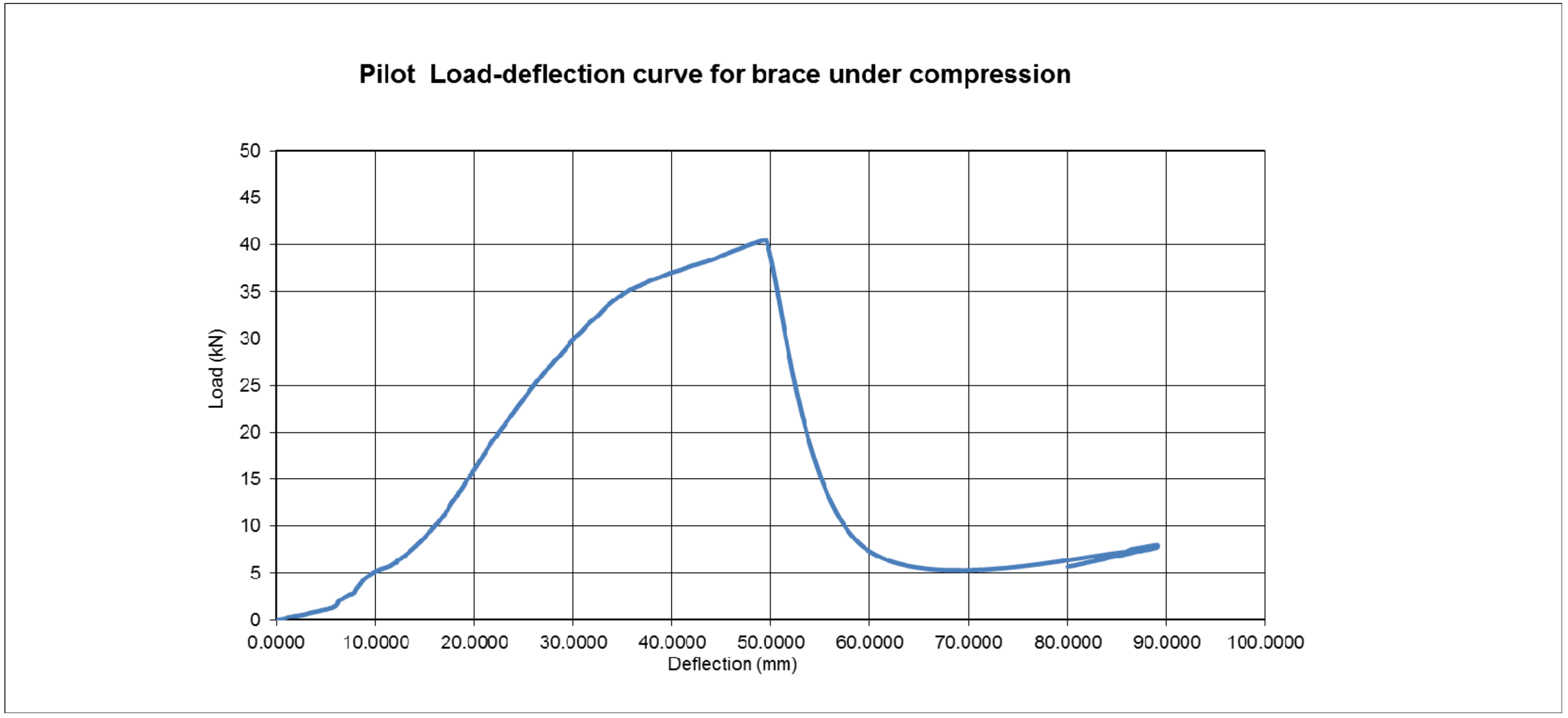

y = -2.162783E+09x6 + 3.536189E+08x5 - 2.126868E+07x4 + 5.665088E+05x3 - 7.070785E+03x2 + 1.135415E+02x
R² = 9.959273E-01
Moment-rotation Curve for the Transom/standard Test 2
Inverted Configuration
Moment (kNm)
Rotation (rad)
3
2
1
0
-1
-2
-3
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25

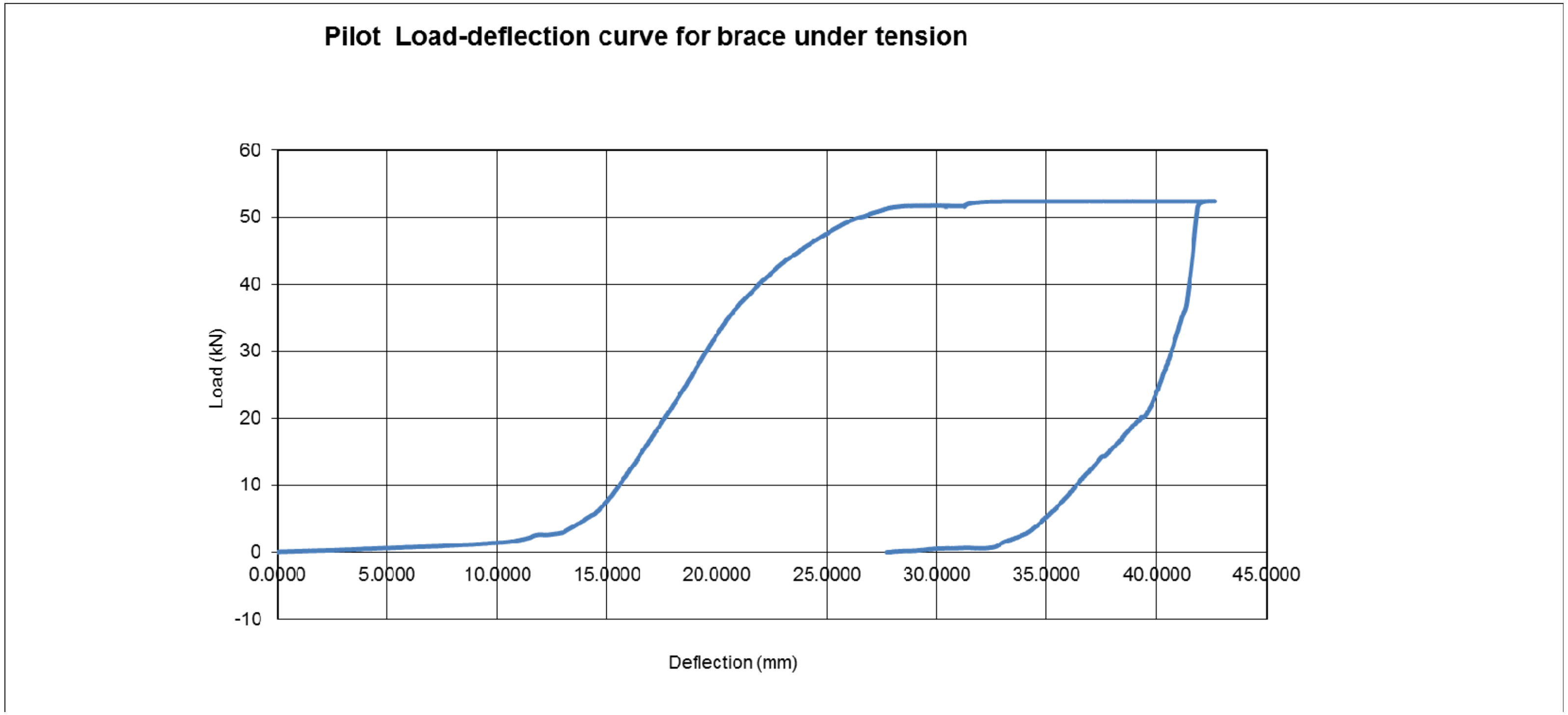


y = 1.925808E+07x6 - 6.794884E+06x5 + 8.909520E+05x4 - 4.827549E+04x3 + 1.625192E+02x2 + 9.461066E+01x
R² = 9.981524E-01
Moment-rotation Curve for the Transom/standard Test 3
Inverted Configuration
Moment (kNm)
Rotation (rad)
4
3
2
1
0
-1
-2
-3
-0.1
-0.05
0
0.05
0.1
0.15
0.2

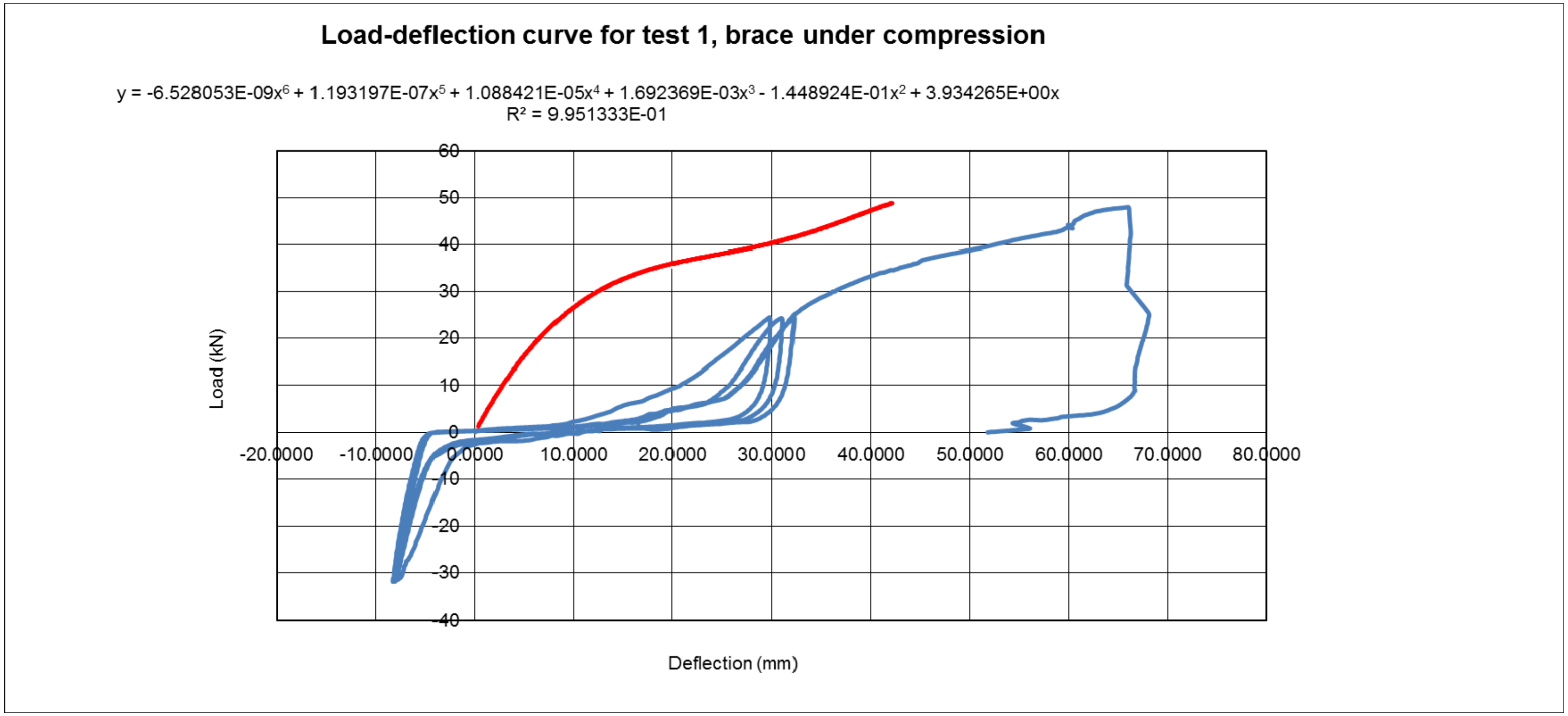
Appendix 3: Load-deflection curves for brace assemblies

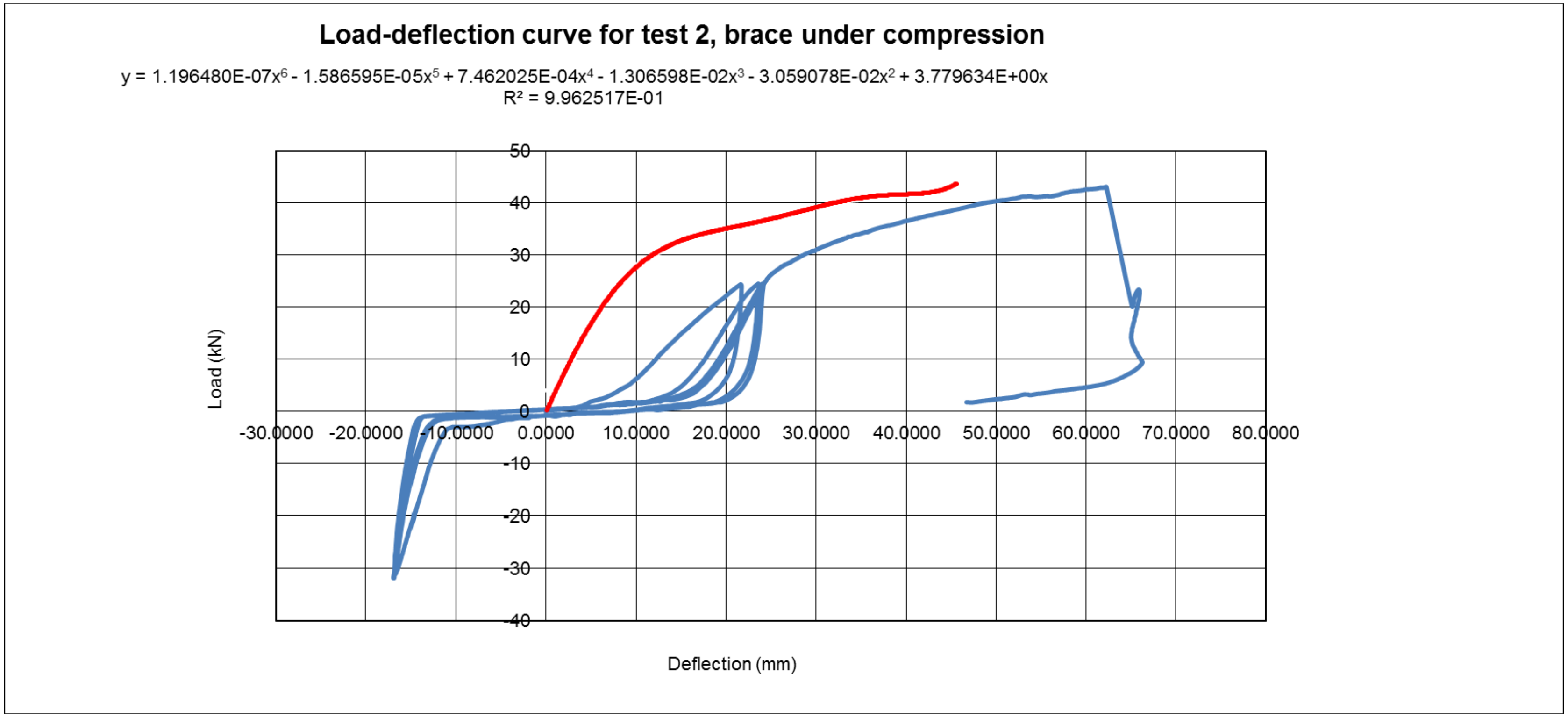
(a) Initial tests to failure

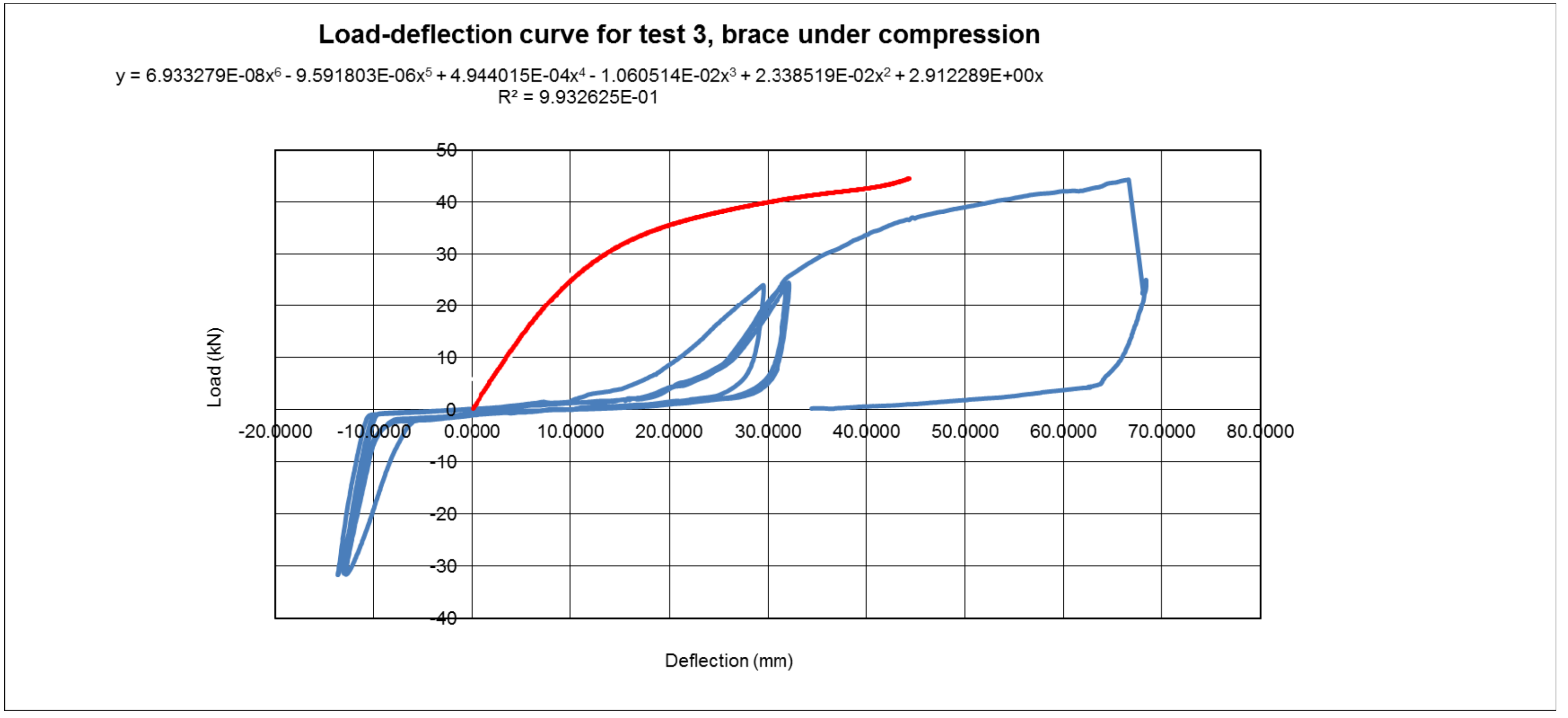


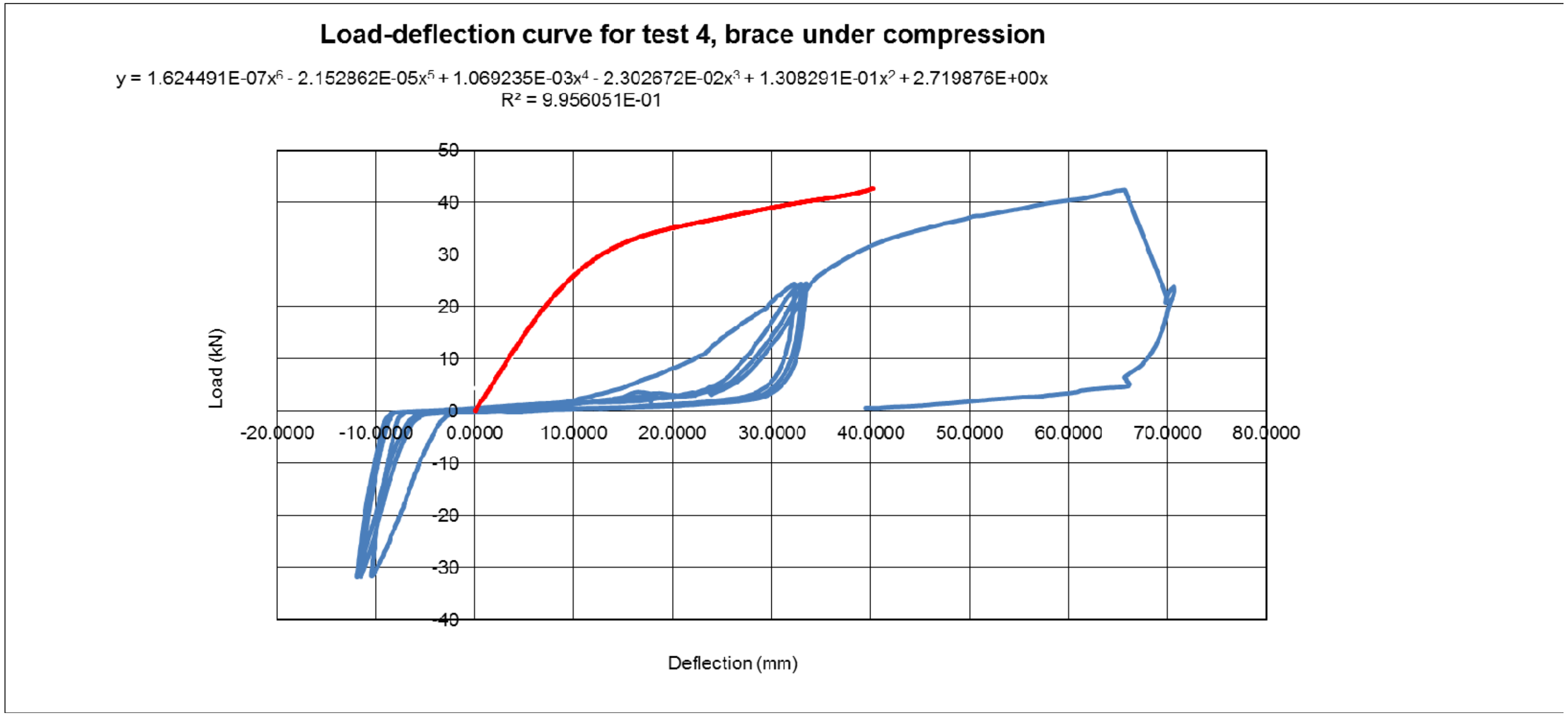

Pilot Load-deflection curve for brace under tension
60
50
40
30
20
10
0
-10
Load (kN)
0.0000
5.0000
10.0000
15.0000
20.0000
25.0000
30.0000
35.0000
40.0000
45.0000
Deflection (mm)

(b) Cyclic tests on brace assemblies- - brace in compression

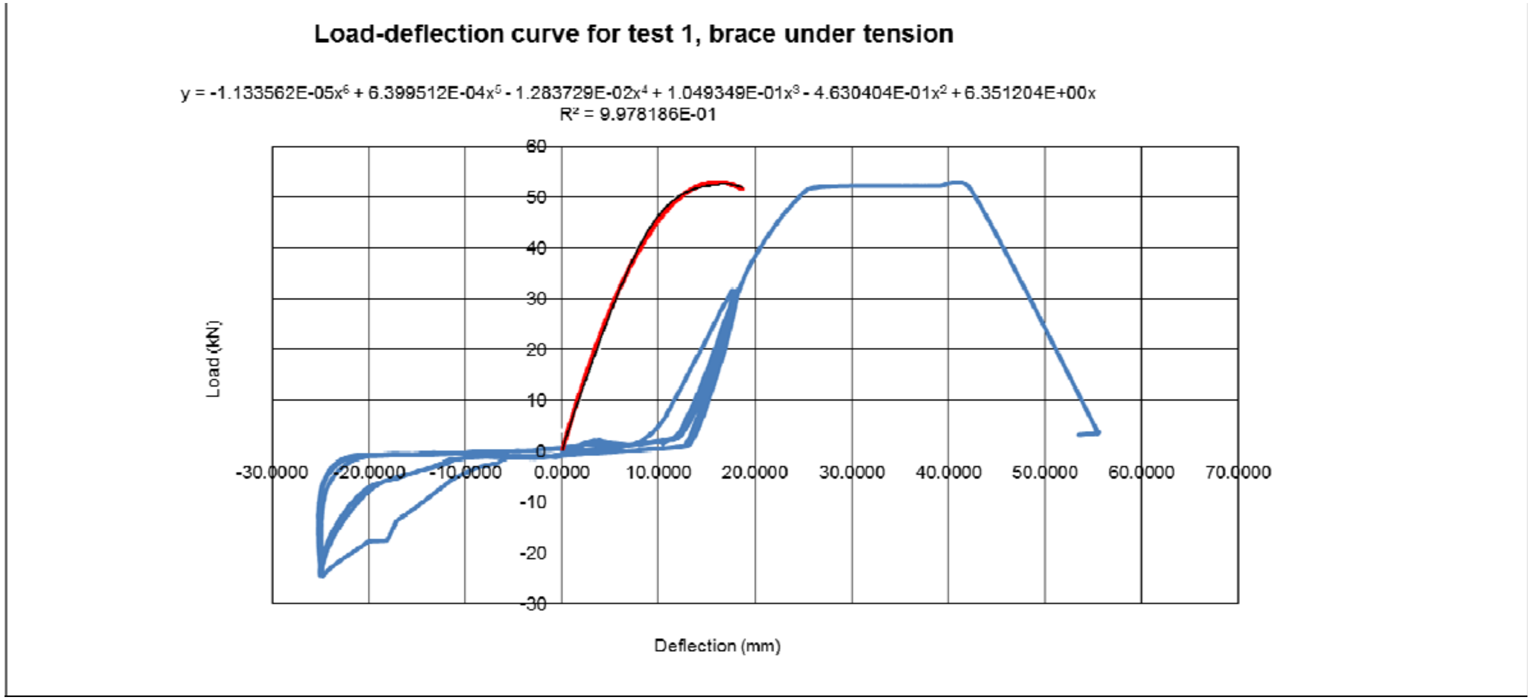


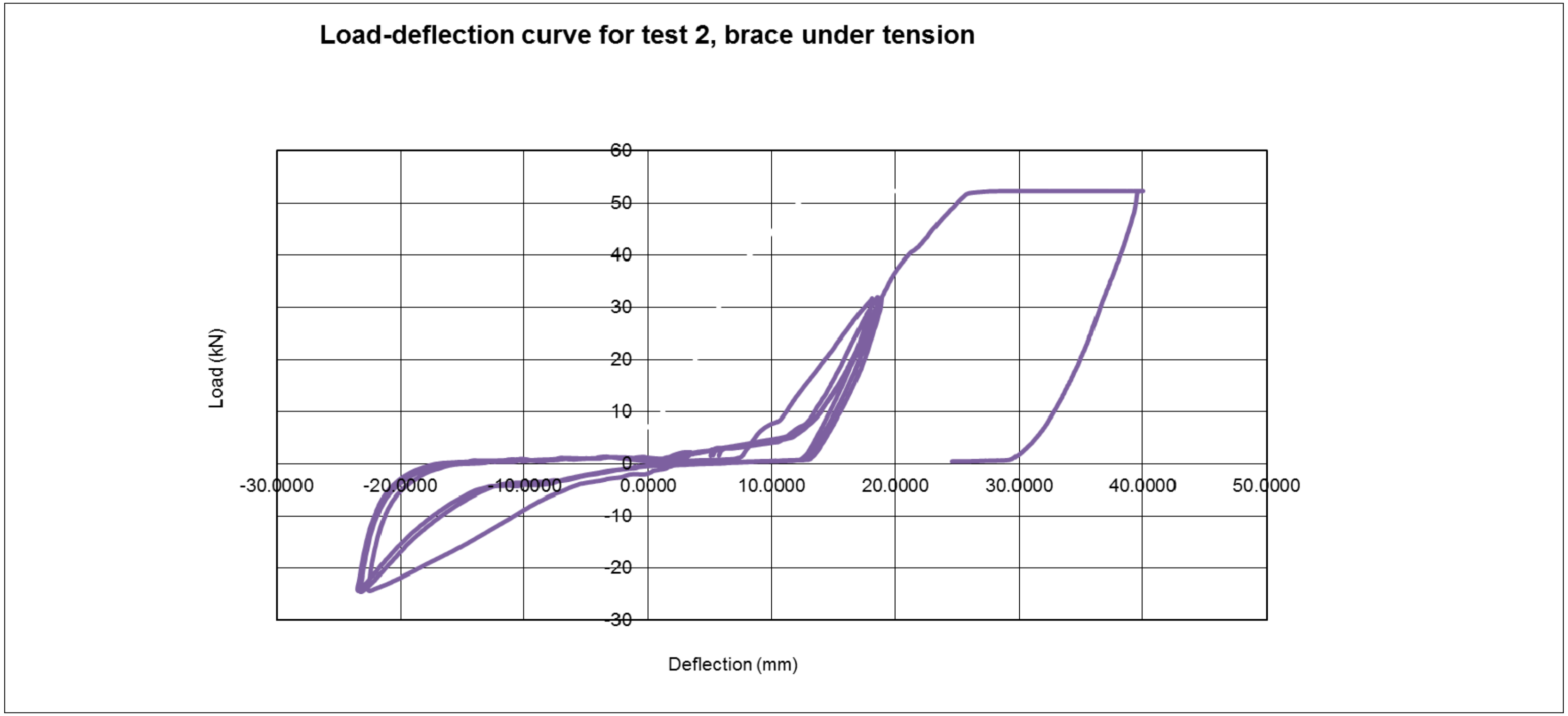

Load-deflection curve for test 2, brace under compression
y = 1.196480E-07x⁶ - 1.586595E-05x⁵ + 7.462025E-04x⁴ - 1.306598E-02x³ - 3.059078E-02x² + 3.779634E+00x
R² = 9.962517E-01
Load (kN)
Deflection (mm)
50
40
30
20
10
0
-10
-20
-30
-40
-30.0000
-20.0000
-10.0000
0.0000
10.0000
20.0000
30.0000
40.0000
50.0000
60.0000
70.0000
80.0000


Load-deflection curve for test 3, brace under compression
y = 6.933279E-08x⁶ - 9.591803E-06x⁵ + 4.944015E-04x⁴ - 1.060514E-02x³ + 2.338519E-02x² + 2.912289E+00x
R² = 9.932625E-01
Load (kN)
50
40
30
20
10
0
-10
-20
-30
-40
-20.0000
-10.0000
0.0000
10.0000
20.0000
30.0000
40.0000
50.0000
60.0000
70.0000
80.0000
Deflection (mm)

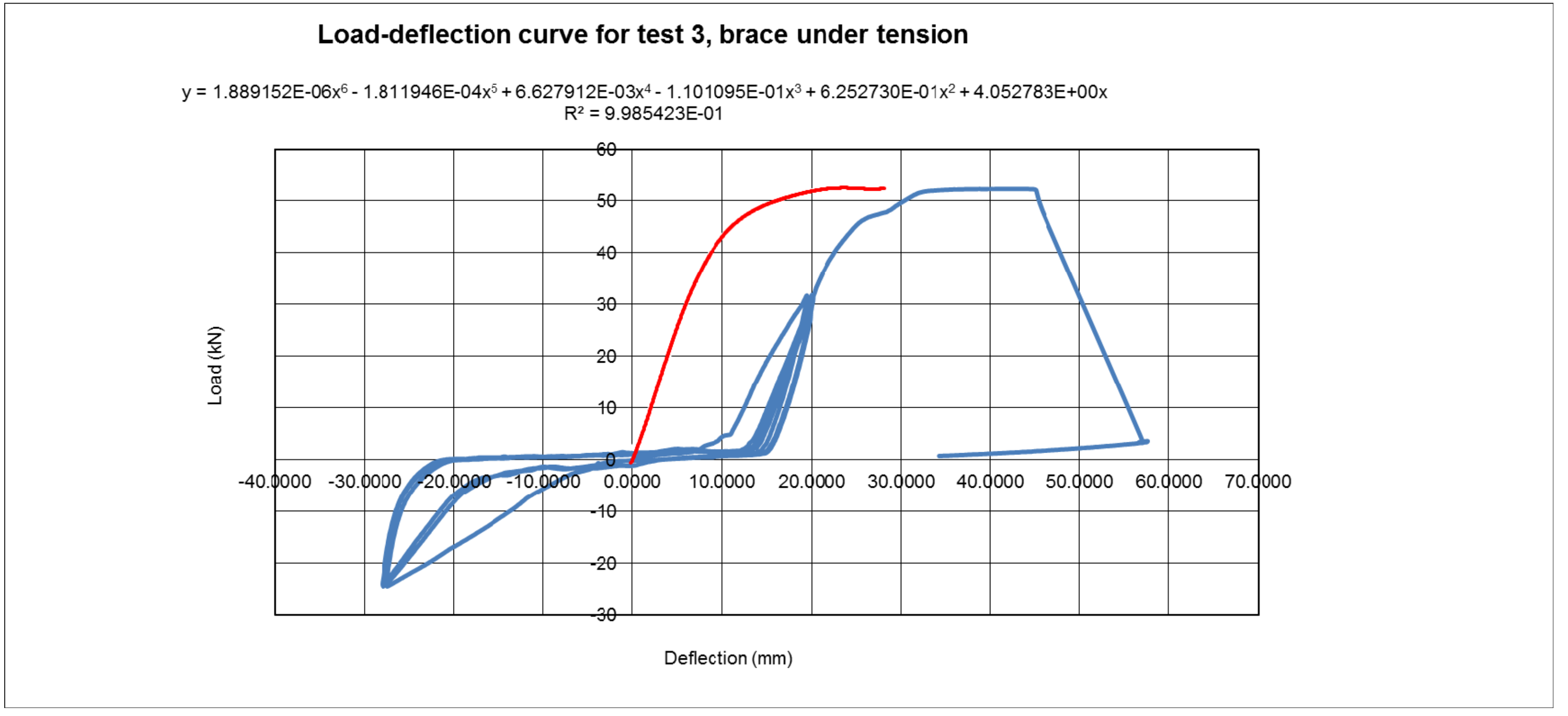

Load-deflection curve for test 4, brace under compression
y = 1.624491E-07x⁶ - 2.152862E-05x⁵ + 1.069235E-03x⁴ - 2.302672E-02x³ + 1.308291E-01x² + 2.719876E+00x
R² = 9.956051E-01
50
40
30
20
10
0
-10
-20
-30
-40
-20.0000
-10.0000
0.0000
10.0000
20.0000
30.0000
40.0000
50.0000
60.0000
70.0000
80.0000
Load (kN)
Deflection (mm)

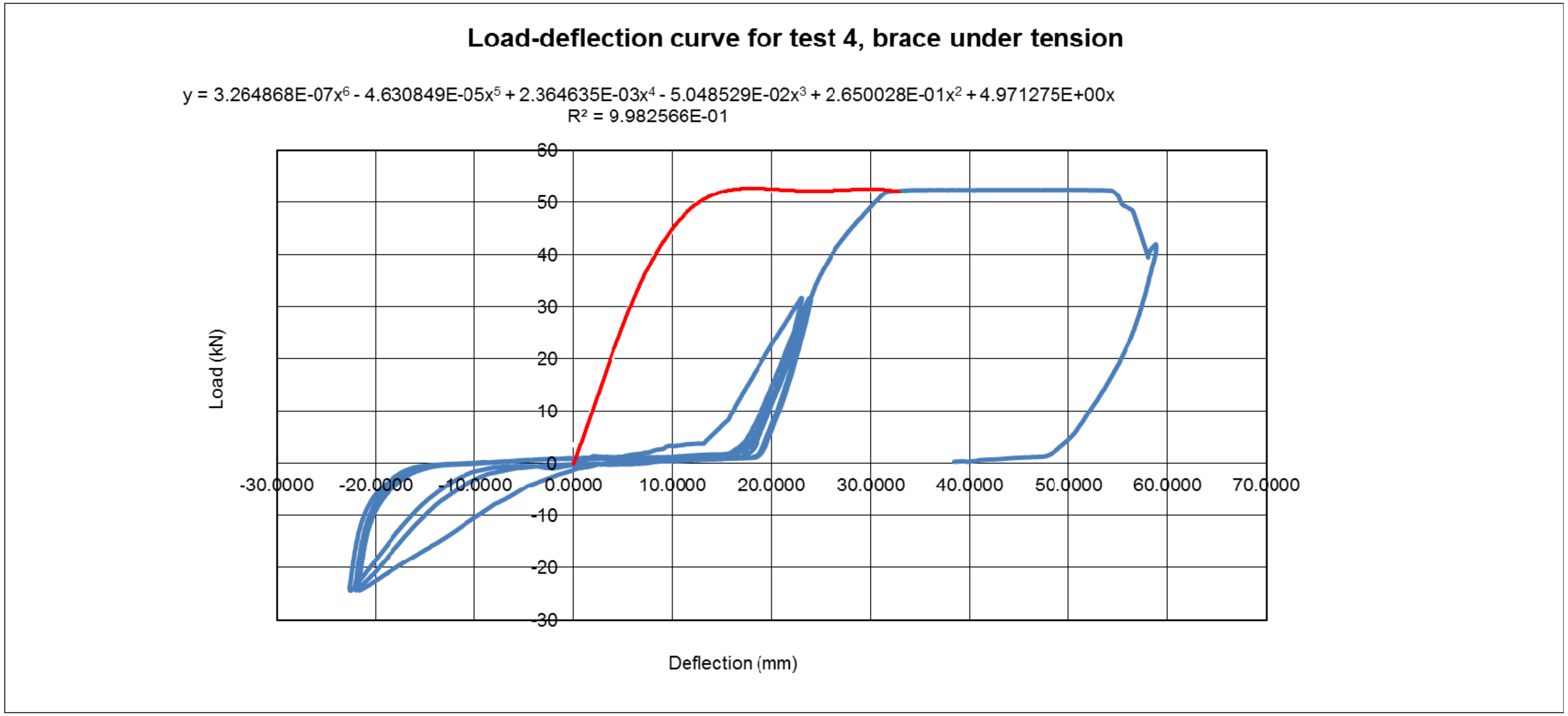
(c) Cyclic tests on brace assemblies – brace in tension





Load-deflection curve for test 2, brace under tension
Load (kN)
60
50
40
30
20
10
0
-10
-20
-30
-30.0000
-20.0000
-10.0000
0.0000
10.0000
20.0000
30.0000
40.0000
50.0000
Deflection (mm)


Load-deflection curve for test 3, brace under tension
y = 1.889152E-06x6 - 1.811946E-04x5 + 6.627912E-03x4 - 1.101095E-01x3 + 6.252730E-01x2 + 4.052783E+00x
R² = 9.985423E-01
Load (kN)
Deflection (mm)
60
50
40
30
20
10
0
-10
-20
-30
-40.0000
-30.0000
-20.0000
-10.0000
0.0000
10.0000
20.0000
30.0000
40.0000
50.0000
60.0000
70.0000



Load-deflection curve for test 4, brace under tension
y = 3.264868E-07x6 - 4.630849E-05x5 + 2.364635E-03x4 - 5.048529E-02x3 + 2.650028E-01x2 + 4.971275E+00x
R² = 9.982566E-01
Load (kN)
60
50
40
30
20
10
0
-10
-20
-30
-30.0000
-20.0000
-10.0000
0.0000
10.0000
20.0000
30.0000
40.0000
50.0000
60.0000
70.0000
Deflection (mm)

Appendix 4: Vibration test results

Tests done using a sine wave with amplification of 0.5 kN, mean 0.0 kN, frequency 2.5 Hz, pump pressure 500 PSI under load control

Test Number	Test file	Number of cycles	Comment
1	J646LV1	6201	After about 4500 cycles amplitude of LVDT 4 changed from 1.04 to 1.60 mm but settled down to 1.20 at end. Joint was tight after testing (6200 cycles)
2	J646LV2	6200	Amplitude LVDT 4 stayed around 1.01 mm throughout. Joint tight after testing (6200) cycles
4	J646LV3	6200	Amplitude LVDT 4 1.89 mm after 101 cycles, 0.91 mm after 500 cycles, 0.94 mm after 2365 cycles, 0.95 mm after 6200 cycles. Joint tight after testing
12	J646TV1	6200	Amplitude LVDT 4 1.32 mm after 192 cycles, 1.24 mm after 995 cycles, 2.15 mm after 3095 cycles and 2.67 mm after 6200 cycles. Joint tight after testing.
13	J624TV2	6200	Amplitude LVDT 4 0.55 mm after 102 cycles, 0.46 mm after 3099 cycles, 0.34 mm after 6200 cycles. Joint tight after testing.
15	J624TV3	6200	Amplitude LVDT 4 after 104 cycles, 1.06 mm, 0.86 mm after 3100 cycles, 1.24 mm after 6200 cycles. Joint tight after testing

Appendix 5: Tensile test results

(a) Tensile tests on Tubes

Test No.	ULS (*N/mm²*)	ln(ULS)
33004C	575	6.354370
33005C	554	6.317165
33006C	564	6.335054
Min	554	
Mean	564.3	6.335530
Max	575	
StDev	10.5	0.018607

Mean ultimate tensile stress = 564.3 N/mm^2, standard deviation = 10.5 N/mm^2, , design strength = 510 N/mm^2, characteristic strength = 532.1 N/mm^2, adjustment ratio = 0.958

(b) Hardness tests

Bolt (BCC)

Test No.	Hardness	ULS (*N/mm²*)	ln(ULS)
BCC/1B	184.8	629.0	6.444131
BCC/2B	185.0	630.3	6.446196
BCC/3B	202.2	681.8	6.524736
Min		629.0	
Mean	190.6	647.0	6.471688
Max		681.8	
StDev	10.0	30.12	0.045953

Mean ultimate tensile stress = 647.0 N/mm^2, standard deviation = 30.12 N/mm^2, design strength 830 N/mm^2, characteristic strength = 559.4 N/mm^2, adjustment ratio = 1.000

Bottom cup

Test No.	Hardness	ULS (*N/mm²*)	ln(ULS)
LCI/1C	183.8	622.3	6.433422
LCI/2C	210.4	696.5	6.546068
LCI/3C	194.6	654.9	6.484483
Min		622.3	
Mean	196.3	657.9	6.484483
Max		696.5	
StDev	13.4	25.7	0.056405

Mean ultimate tensile stress = 657.9 N/mm^2, standard deviation = 37.2 N/mm^2, design strength = 690 N/mm^2, characteristic strength = 550.2 N/mm^2, adjustment ratio = 1.000

Top cup

Test No.	Hardness	ULS (*N/mm*^{2})	ln(ULS)
BCT/1L	191.2	651.4	6.479124
BCT/2L	189.8	651.1	6.478663
BCT/3L	198.6	665.0	6.499787
Min		651.1	
Mean	193.2	655.8	6.485858
Max		665.0	
StDev	4.7	7.9	0.012065

Mean ultimate tensile stress = 655.8 N/mm^2, standard deviation = 7.9 N/mm^2, design strength = 640 N/mm^2, characteristic strength = 631.3 N/mm^2, adjustment ratio = 1.000

Ledger tongue

Test No.	Hardness	ULS (*N/mm*^{2})	ln(ULS)
LCN/1T	165.2	544.3	6.299501
LCN/2T	160.6	536.2	6.284507
LCN/3T	168.6	550.2	6.310282
Min		536.2	
Mean	164.8	543.6	6.298097
Max		550.2	
StDev	4.0	4.0	0.012945

Mean ultimate tensile stress = 543.6 N/mm^2**,** standard deviation = 7.0 N/mm^2**,** design strength = 520 N/mm^2, characteristic strength = 521.8 N/mm^2, adjustment ratio = 1.000

Weld

Test No.	Hardness	ULS (*N/mm*^{2})	ln(ULS)
TCI/1W	153.8	519.5	6.252867
TCI/2W	206.0	688.9	6.535096
TCI/3W	151.8	514.0	6.242223
Min		514.0	
Mean	170.5	574.1	6.343395
Max		688.9	
StDev	30.7	99.4	0.166103

Mean ultimate tensile stress = 574.1 N/mm^2**,** standard deviation = 99.4 N/mm^2, design strength = 510 N/mm^2, characteristic strength = 337.0 5N/mm^2, adjustment ratio = 1.000

Appendix 6: Westmoreland Mechanical Testing & Research Limited

The PDF is appended to the document (5 pages)

Westmoreland Mechanical Testing & Research, Ltd.

19 Wildmere Road, Banbury
Oxfordshire OX16 3JU, U.K.
Telephone: +44 (0) 1295 261211
Fax: +44 (0) 1295 263096
Website: www.wmtr.co.uk

Accredited Nadcap Materials Testing Laboratory

UKAS TESTING 2616

Oxford Brookes Enterprises Limited
Headington Campus
Gipsy Lane
Headington
Oxfordshire
OX3 0BP
Attention: Mr Ray Salter

Report No: **UK-16000361 Hardness**
Test & Report Date: 15th - 16th March 2016
WMT&R Quote No: QB160242
Purchase Order No: IC421869/TDE
Test Temperature: 22.0°C
Test Operator: TF

Vickers Hardness (HV5)

Fifteen samples were supplied for hardness (Vickers) testing, in order to determine the core hardness. Samples were mounted and prepared in accordance with ASTM E3-11. Hardness testing was performed with a Vickers-Armstrong hardness tester in accordance with ASTM E384-11. No specification or requirement was supplied by the customer. The results in this report relate only to the items tested.

Customer Identity	Test Log No.	Results (HV5)					Average
Bolt BCC/1B	32989C	183	182	188	188	183	185
Bolt BCC/2B	32990C	187	182	183	185	188	185
Bolt BCC/3B	32991C	199	208	199	208	197	202
Cup LCI/1C	32992C	183	183	185	180	188	184
Cup LCI/2C	32993C	210	214	212	210	206	210
Cup LCI/3C	32994C	195	193	195	197	193	195
Locking Ring BCT/1L	32995C	188	188	195	193	192	191
Locking Ring BCT/2L	32996C	195	190	187	192	185	190
Locking Ring BCT/3L	32997C	203	195	203	199	193	199
Ledger Tongue LCN/1T	32998C	160	162	171	158	175	165
Ledger Tongue LCN/2T	32999C	158	156	157	161	171	161
Ledger Tongue LCN/3T	33000C	177	168	165	162	171	169
Weld TCI/1W	33001C	155	152	162	144	156	154
Weld TCI/2W	33002C	206	195	214	192	223	206
Weld TCI/3W	33003C	160	151	157	134	157	152

Table 1 - Vickers Hardness Results

Approved Signatory: Lianne Cook

Lianne Cook – Head of Dept. Metallography
For and on behalf of WMT& R Limited

Westmoreland Mechanical Testing & Research, Ltd.
19 Wildmere Road, Banbury
Oxfordshire OX16 3JU, U.K.
Telephone: +44 (0) 1295 261211
Fax: +44 (0) 1295 263096
Website: www.wmtr.co.uk

UKAS TESTING
2616

Tensile Test Report
Test Conforms to: BS EN ISO 6892-1 :2009

Oxford Brookes Enterprises Ltd
Headington Campus
Gipsy lane
Headington
Oxford
OX3 0BP

Attn: Mr Raymond Salter

Report Number: **UK-16000362 (Tensile)**

Report Date: 17th March 2016
Revision Date N/A
WMTR Quote No: QB160269 Rev 1
Purchase Order No: IC421867/TDE
Material: Steel S355 JOH
Specimen Orientation: As supplied
1st Test Rate: 0.015 strain/min
2nd Test Rate: 0.400 strain/min (over Lc)
Test Date: 17th March 2016
Operator Initials: AI

The specimens were of nominal width 6.0mm and parallel length (Lc) 32.0mm, marked with a 25.0mm gauge length for determination of elongation.

The specimens were instrumented with a dual averaging extensometer and tested at ambient temperature

The specimens were tested in strain rate control at the first rate to beyond yield at which point the second rate was adopted and the extensometry was removed.

Full details of the testing and equipment used are contained in the laboratory customer folder.

The results in this report relate only to the items tested.

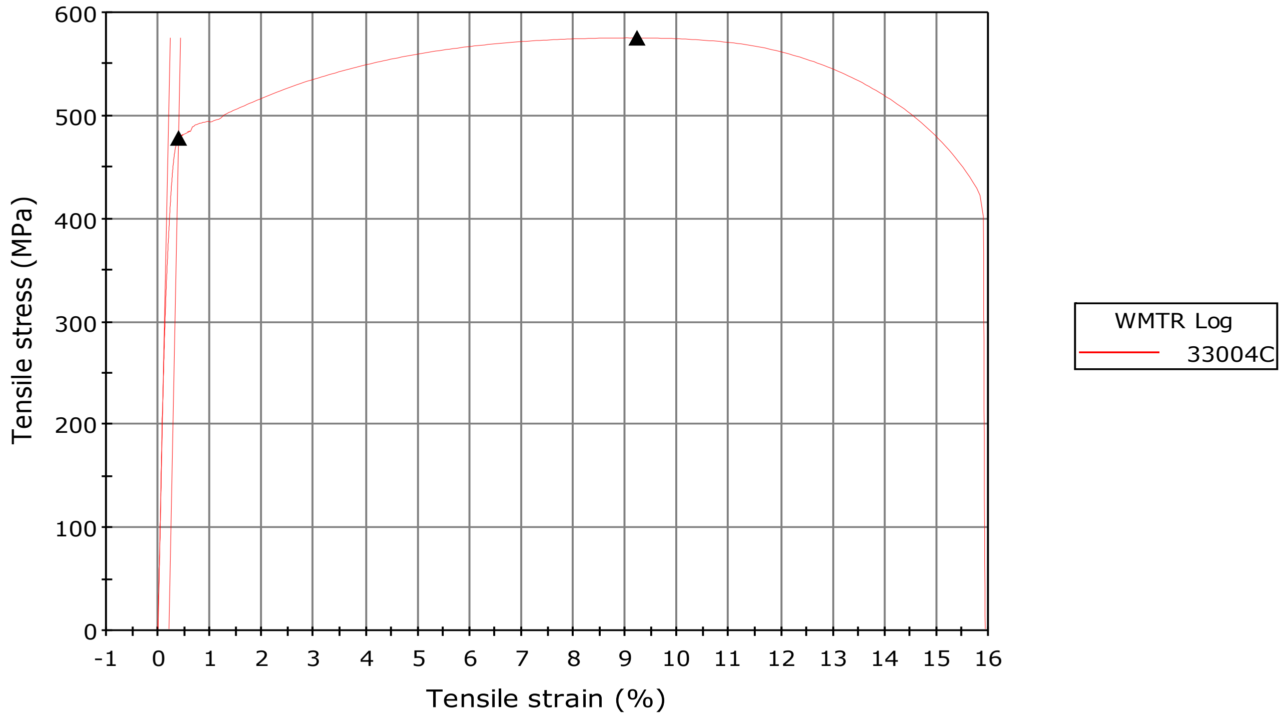
Testlog	Sample Id	0.2% PS (MPa)	UTS (MPa)	Elong. (%)
33004C	BCT/1S	478	575	17.0 *
33005C	BCT/2S	461	554	17.3 *
33006C	BCT/3S	478	564	16.2 *

** Indicates if the specimen broke outside the middle 1/3 of the gauge length.*

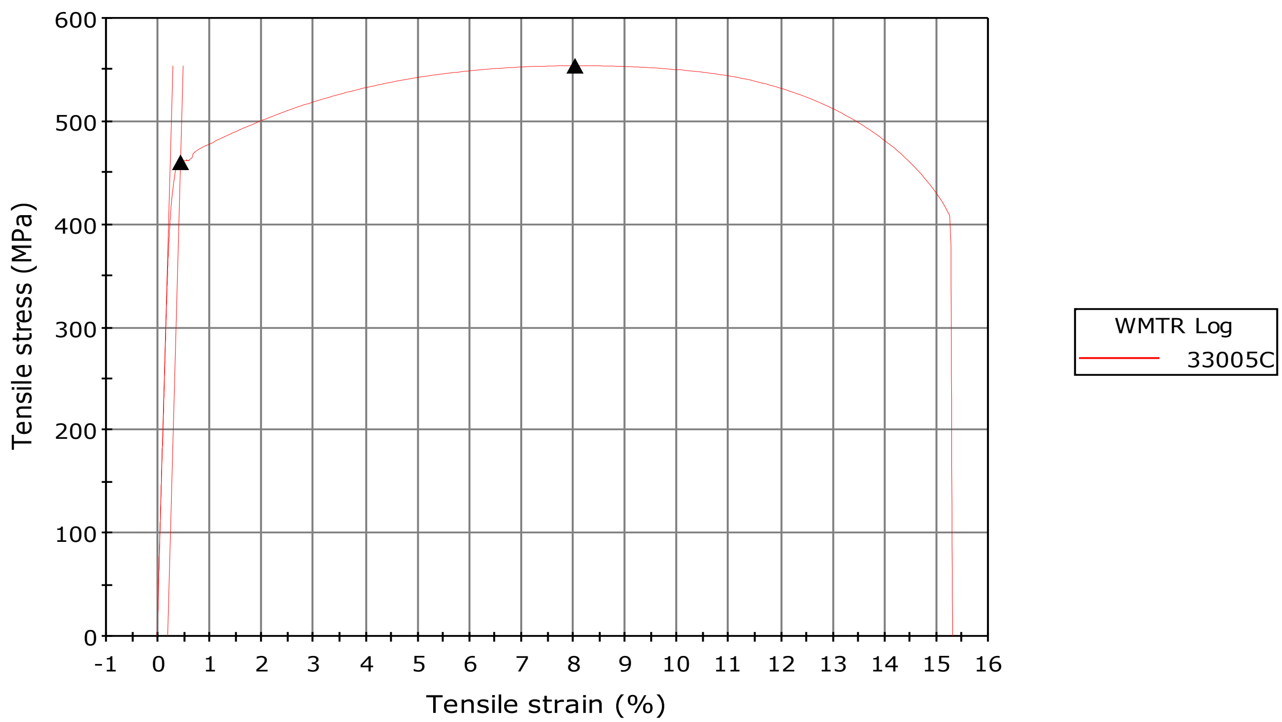
Approved Signatory: Alan Ip

Alan Ip - Technician
For and on behalf of WMT&R Ltd

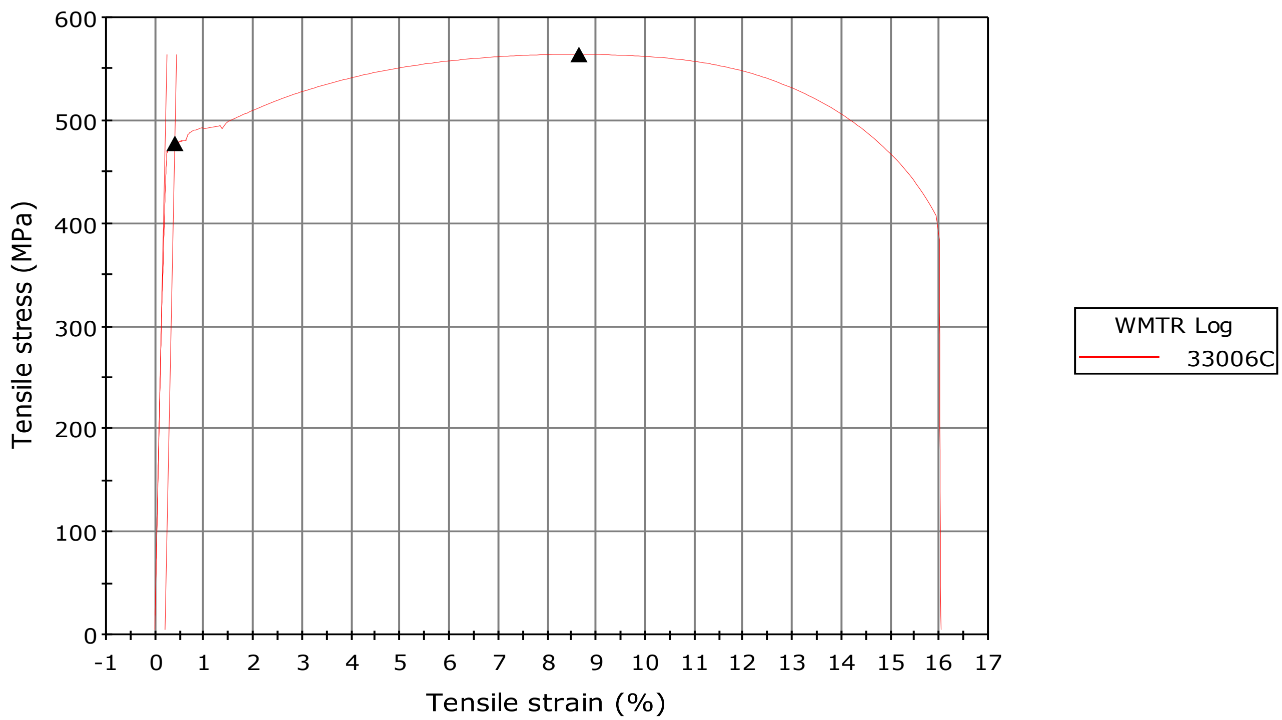
Full Stress-Strain Plot



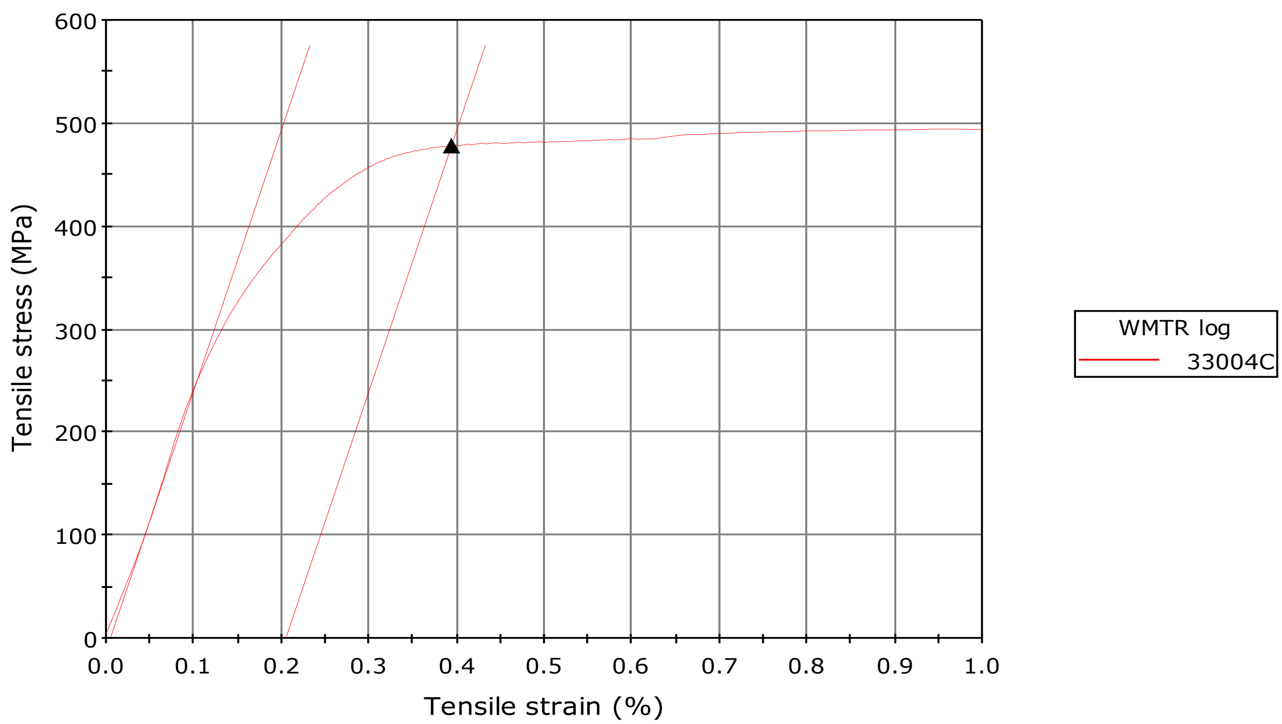
Full Stress-Strain Plot

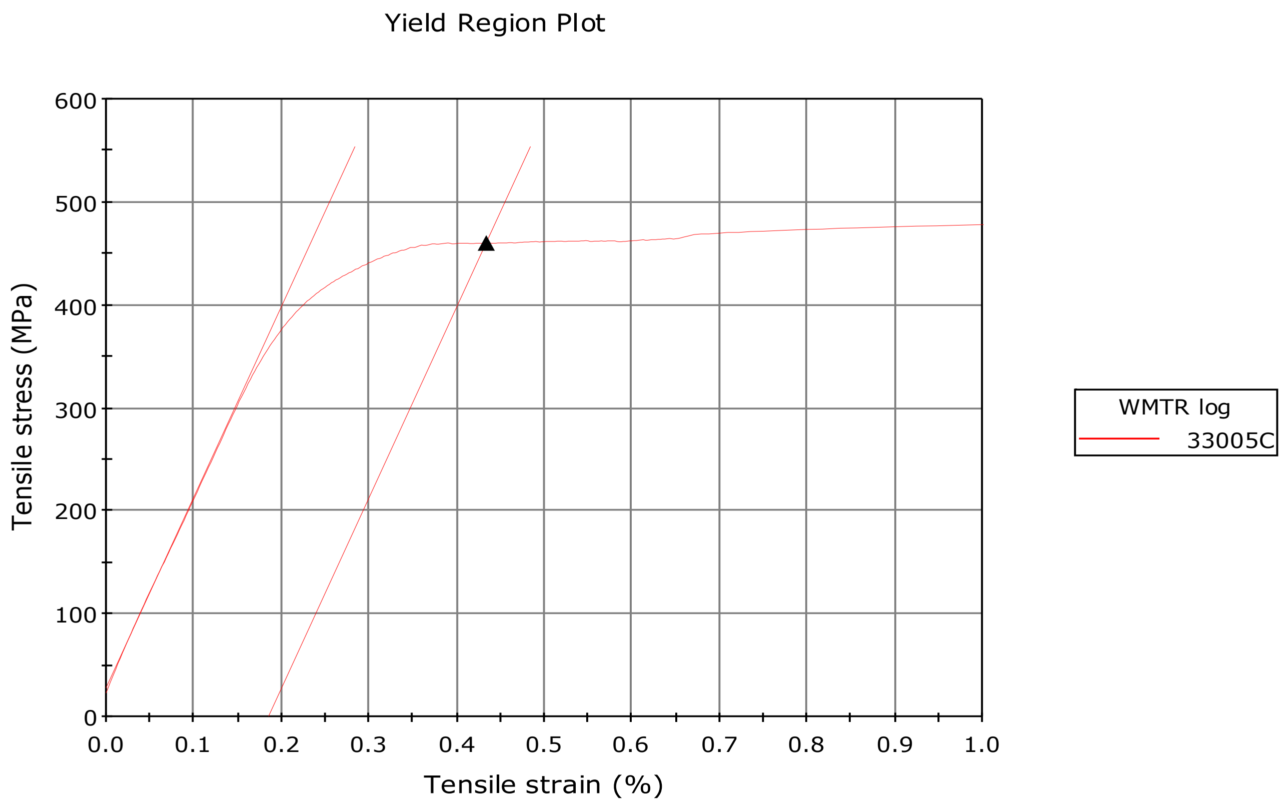


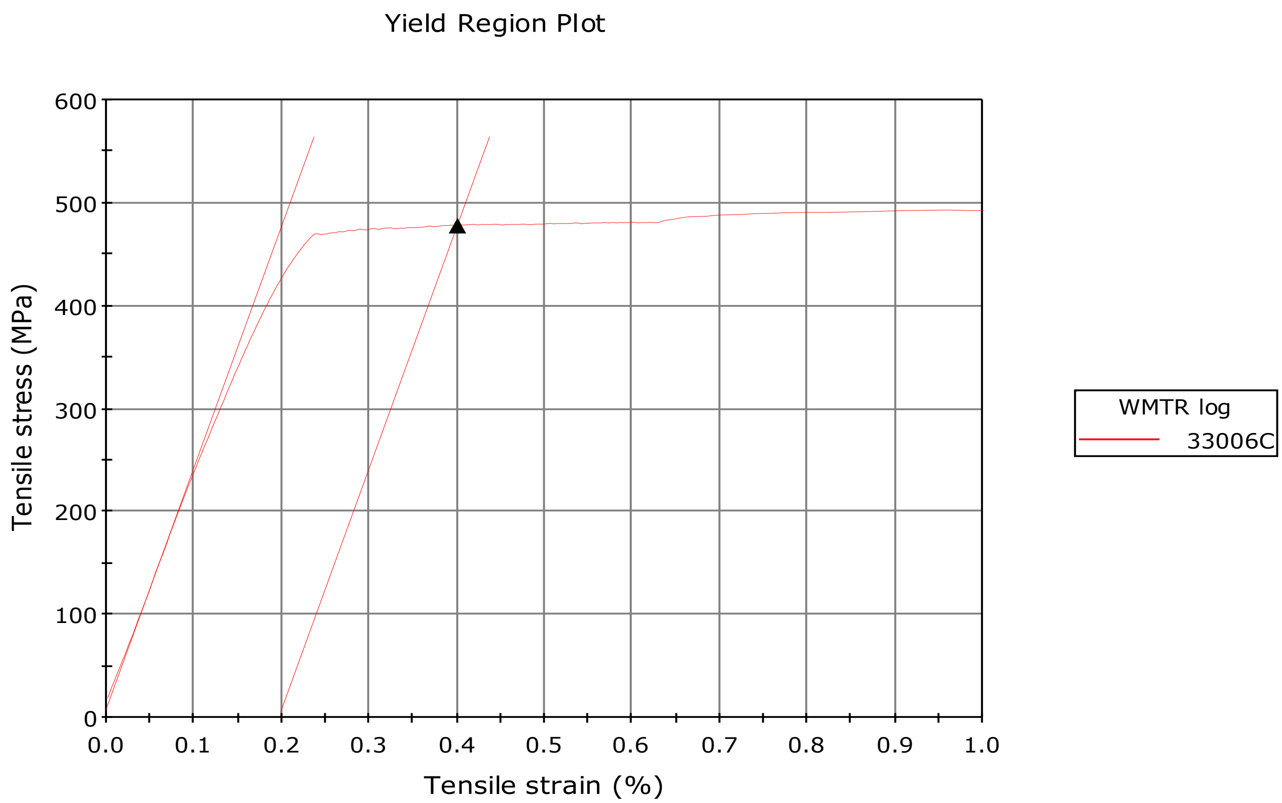
Full Stress-Strain Plot



Yield Region Plot




Yield Region Plot
600
500
400
300
200
100
0
Tensile stress (MPa)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Tensile strain (%)
WMTR log
33005C


Yield Region Plot
600
500
400
300
200
100
0
Tensile stress (MPa)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Tensile strain (%)
WMTR log
33006C