LNWR “George the Fifth” Coupling Rod Design for the Modern Railway

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LNWR GEORGE THE FIFTH
STEAM LOCOMOTIVE TRUST

History Lesson #1

- 1903 George Whale becomes CME
- LNWR desperately needs modern, reliable locos
- April 1904 first “Precursor” enters traffic
- By April 1906 over 100 in traffic
- Simple and rugged - the quintessential British 4-4-0
- He was a Jolly Good Chap

Whale "Precursor" 4-4-0

History Lesson #2

- Charles Bowen-Cooke – LNWR CME in 1909
- Another Jolly Good Chap
- Listens to Wilhelm Schmidt and tries out:
  - Superheat
  - Piston valves
- Applied to an improved “Precursor”, result:
- “George the Fifth” class – June 1910

Bowen-Cooke “George the Fifth”

Technical Bits

- Precursor:
  - 19” cylinders, 175 psi
- George:
  - 20” (later 20.5”) cylinders, 175 psi, (later 180 psi)
- TE increased by 20%
- Running gear essentially identical
- Capable of 1200 IHP (max 1400 IHP)
- 350t @ 60mph average (max 80+ mph)

No. 2013 “Prince George”

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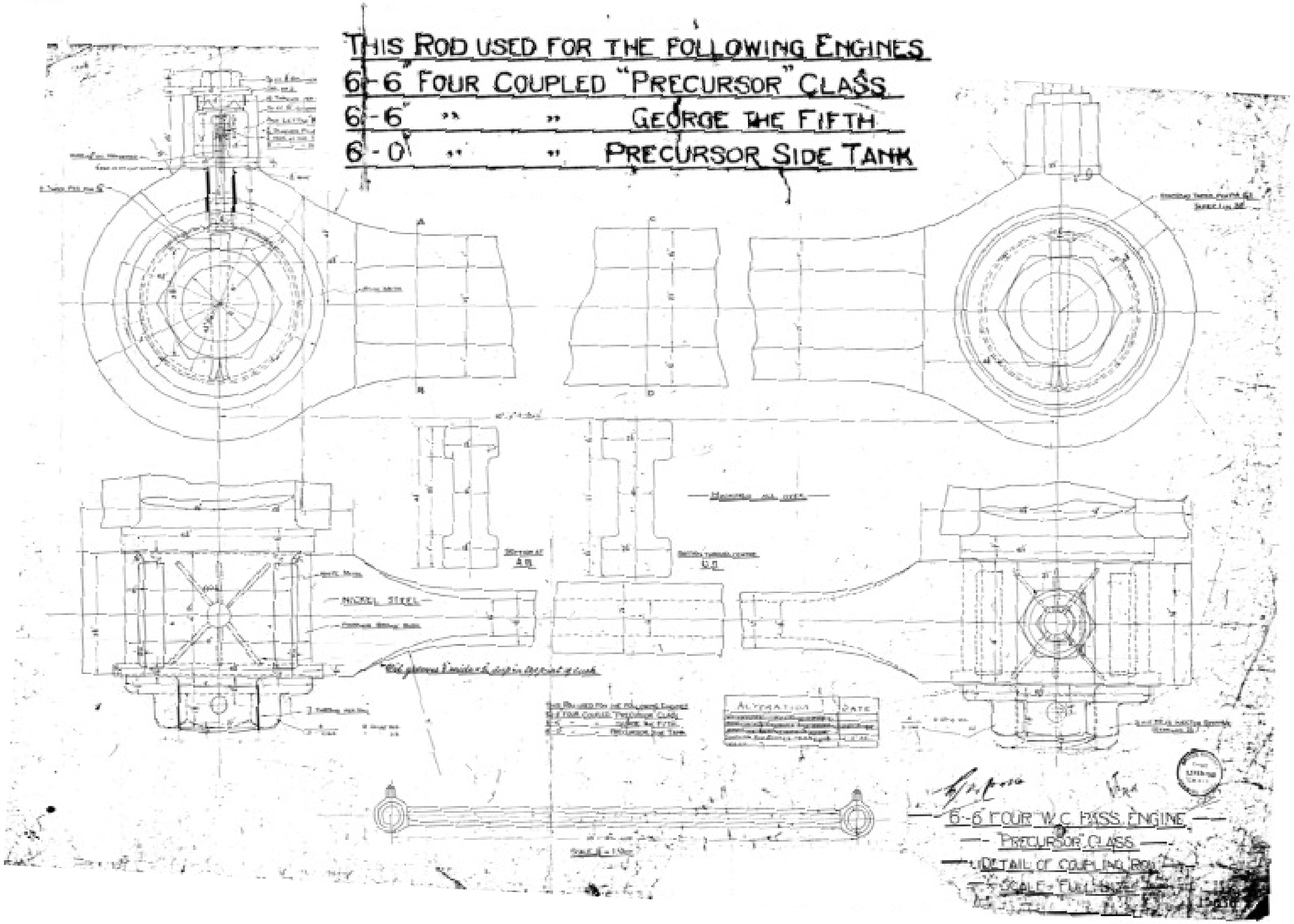
- The Essence of the original build
- Performance ultimately limited by grate area
- Discrete enhancements:
  - 200 psi boiler pressure
  - Axle load 21000 kg axle load
- TE 11% more than original “George”
- 33% more than “Precursor”
- Design for 90 mph (+10% overspeed)

Approvals

- Comply if you can!
- GM/RT 2100 Iss 5
  - 4.4 Equipment Attached to Axleboxes
- Proof Load Case:
  - Longitudinal (x) +/- 10g
  - Transverse (y) +/- 10g
  - Vertical (z) +/- 70g
- Fatigue Load Case, 10^7 cycles:
  - Lateral (y) +/- 5g
  - Vertical (z) +/- 25g

Original Rod



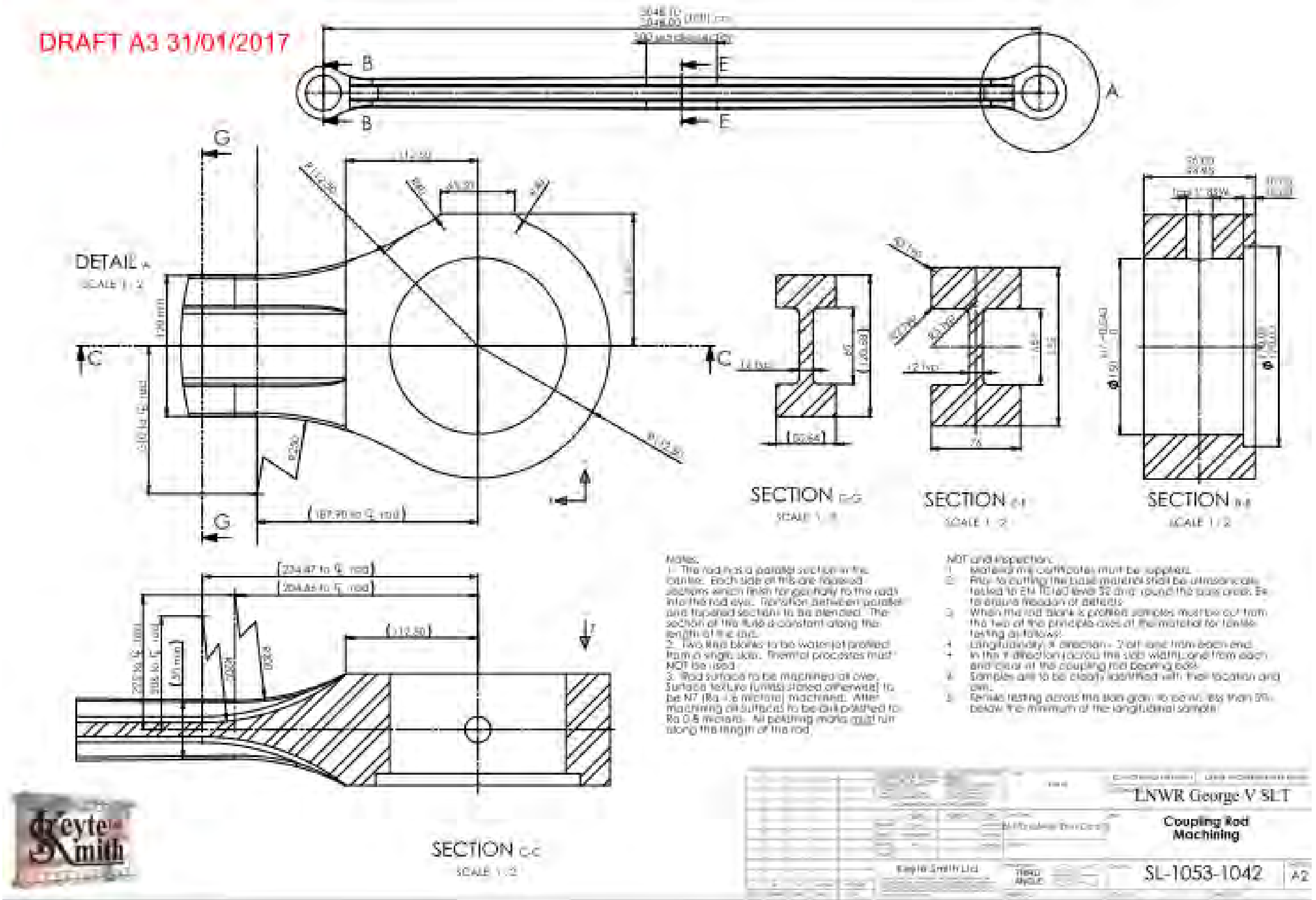
Proof Load Case 1

- Maximum Buckling Load – highest of:
  - Maximum force transmitted due to wheel/rail friction (208.6 kN)
  - Maximum Piston thrust with momentary slip on leading axle (318.1 kN)
- Simple calculation (Euler): $F_b=\pi^2 E.I_{yy} / L^2$
- Original rod: F_b=242 kN
- Rod section redesigned

The Lesson

Just because someone has done it before and got away with it, never assume it will be OK for you.

Rod Redesign

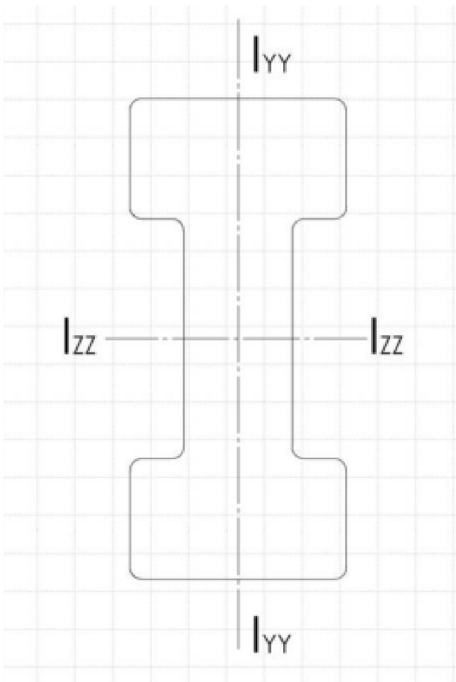


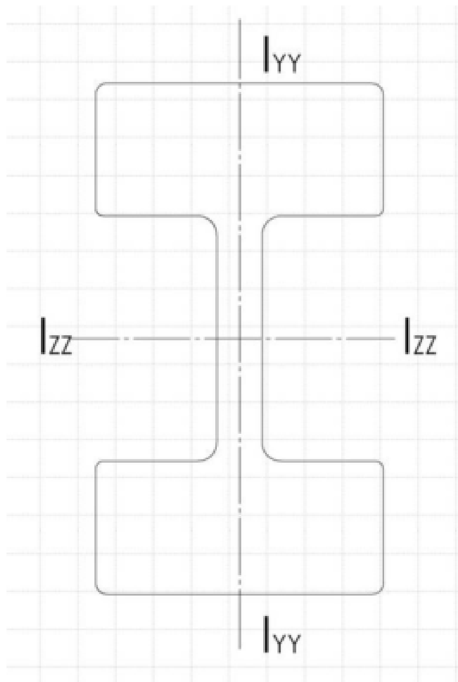
Rod Redesign

- Material in fluted section redistributed
  - Deeper Section
  - Thicker Flanges
  - Greater Flange Width
  - Thinner Web
- Minimal visual impact
- Mass exactly the same (144 kg)
- En 16S material

Rod Redesign

Original	New	Dif
$I_{yy} = 1099533mm^4$	$I_{yy} = 2532584mm^4$	230%
$I_{zz} = 9110259mm^4$	$I_{zz} = 14098241mm^4$	155%





Proof Load Case 2

or

This is where it gets interesting!

- At bottom quadrant:
- Track Forces
  - Upwards (both ends) 70g = 687 m/s^2
  - Lateral (both ends) 10g = 98.1 m/s^2
- 100 mph (90mph + 10% overspeed)
  - 7.14 rev/sec
  - Centripetal acceleration = 614 m/s^2
- Piston Thrust
  - 254.5 kN (80% boiler pressure, front axle slip)

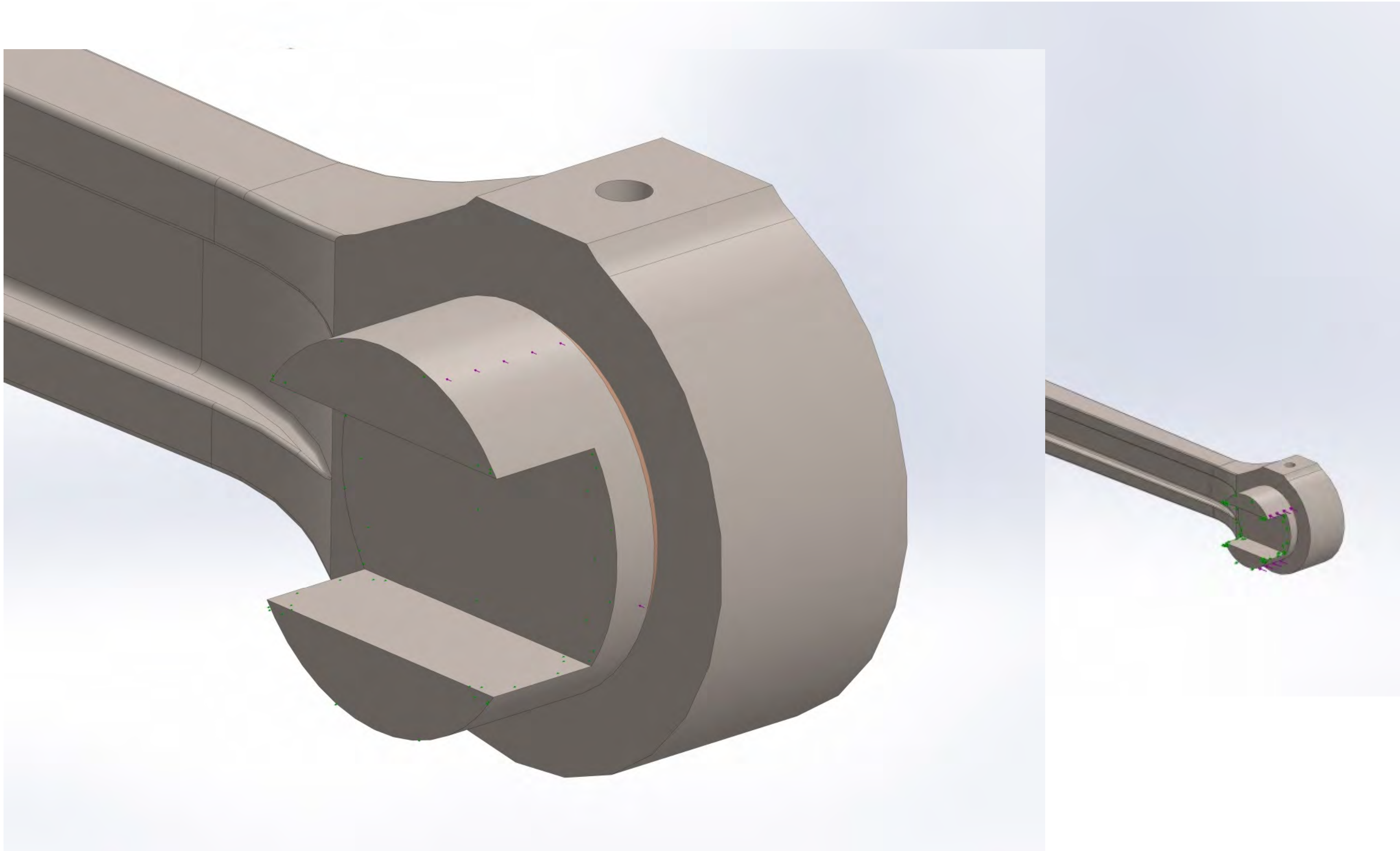
Reality Check!

- Total Upward Acceleration = 1300.3 m/s^2
  - 132.5g
  - If constant acceleration:
    0.26 seconds to break sound barrier!

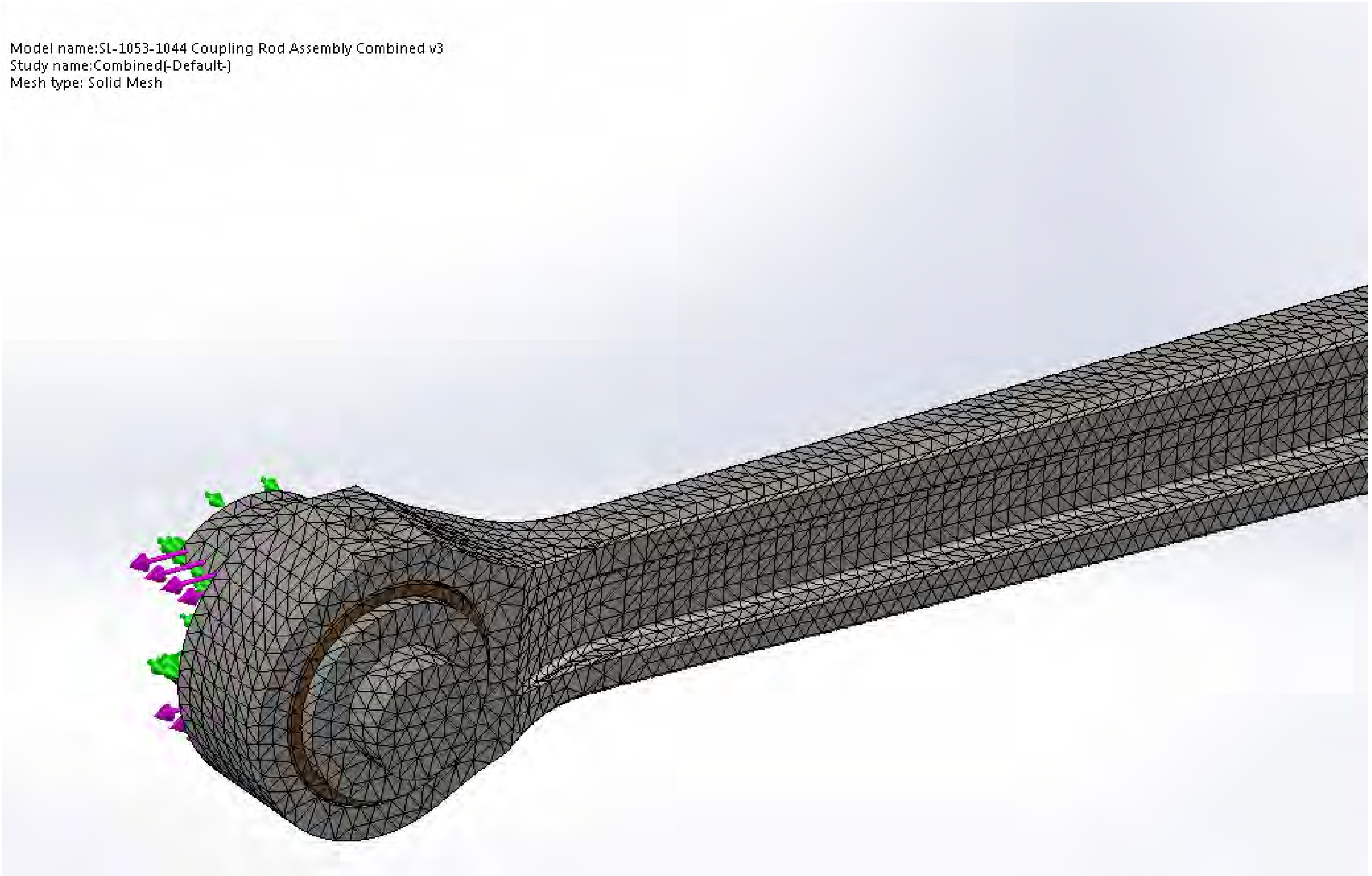
Analysis

- 3D CAD model – SolidWorks 2014
- Integral FEA package
- Modelled as an assembly
  - Bronze bushes - press fit
  - Dummy crankpins – radial clearance
  - Accurate constraints
- Quality of the output depends on quality of the input.

FEA Constraints

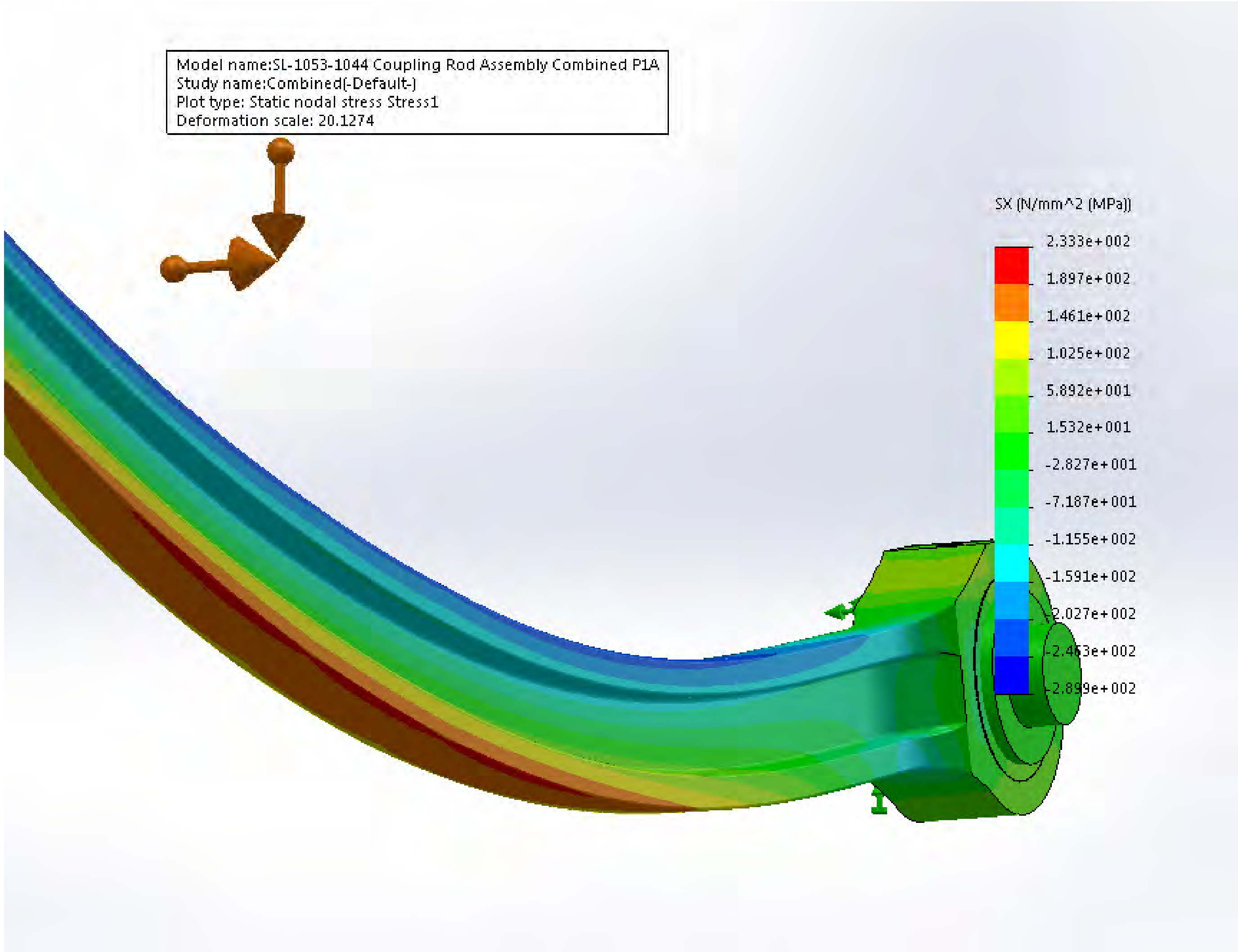


FEA Mesh

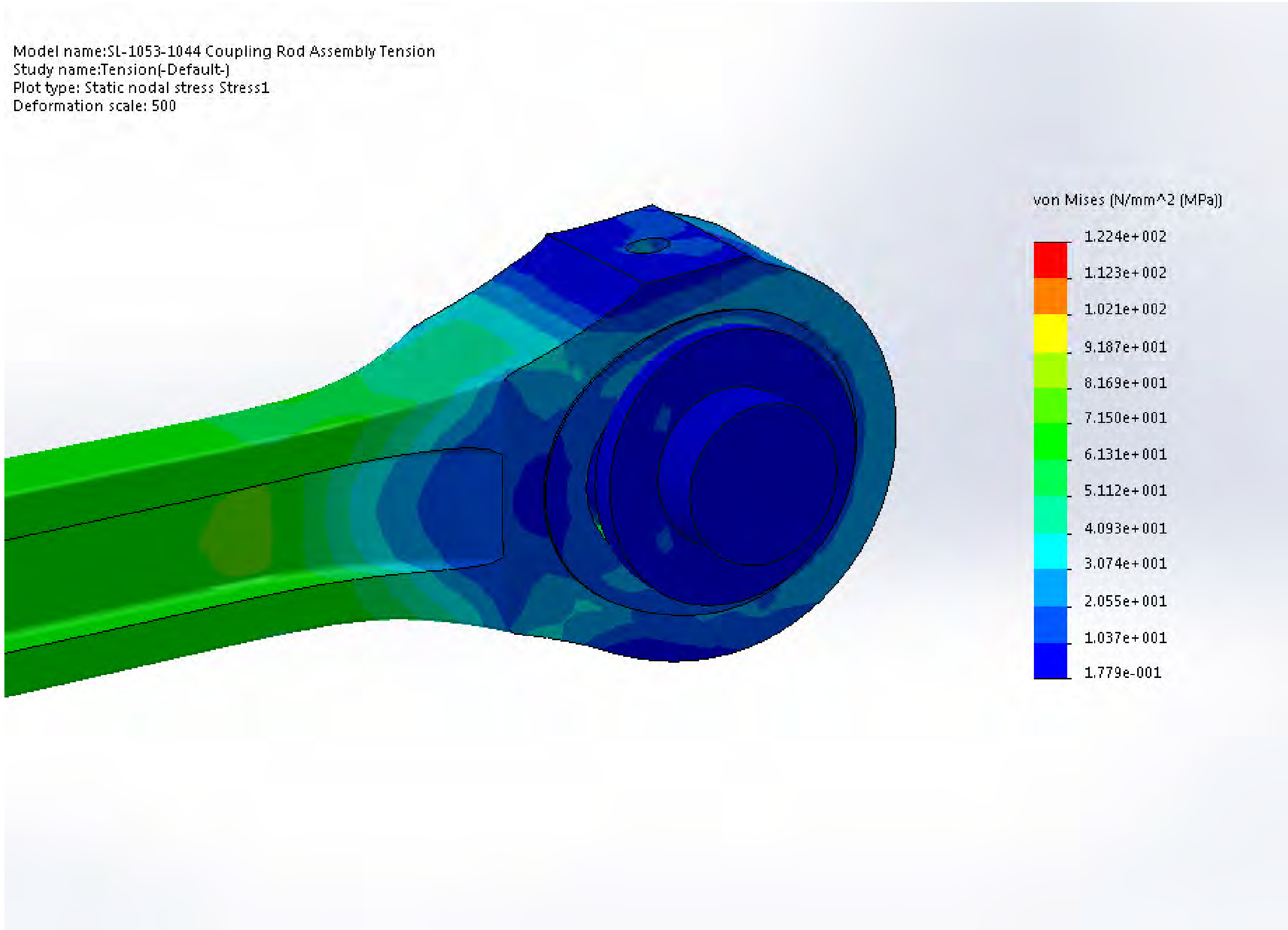


Model name:SL-1053-1044 Coupling Rod Assembly Combined v3
Study name:Combined(-Default-)
Mesh type: Solid Mesh

FEA Analysis – Proof Load Case 2



FEA Analysis – 254.5 kN Tension



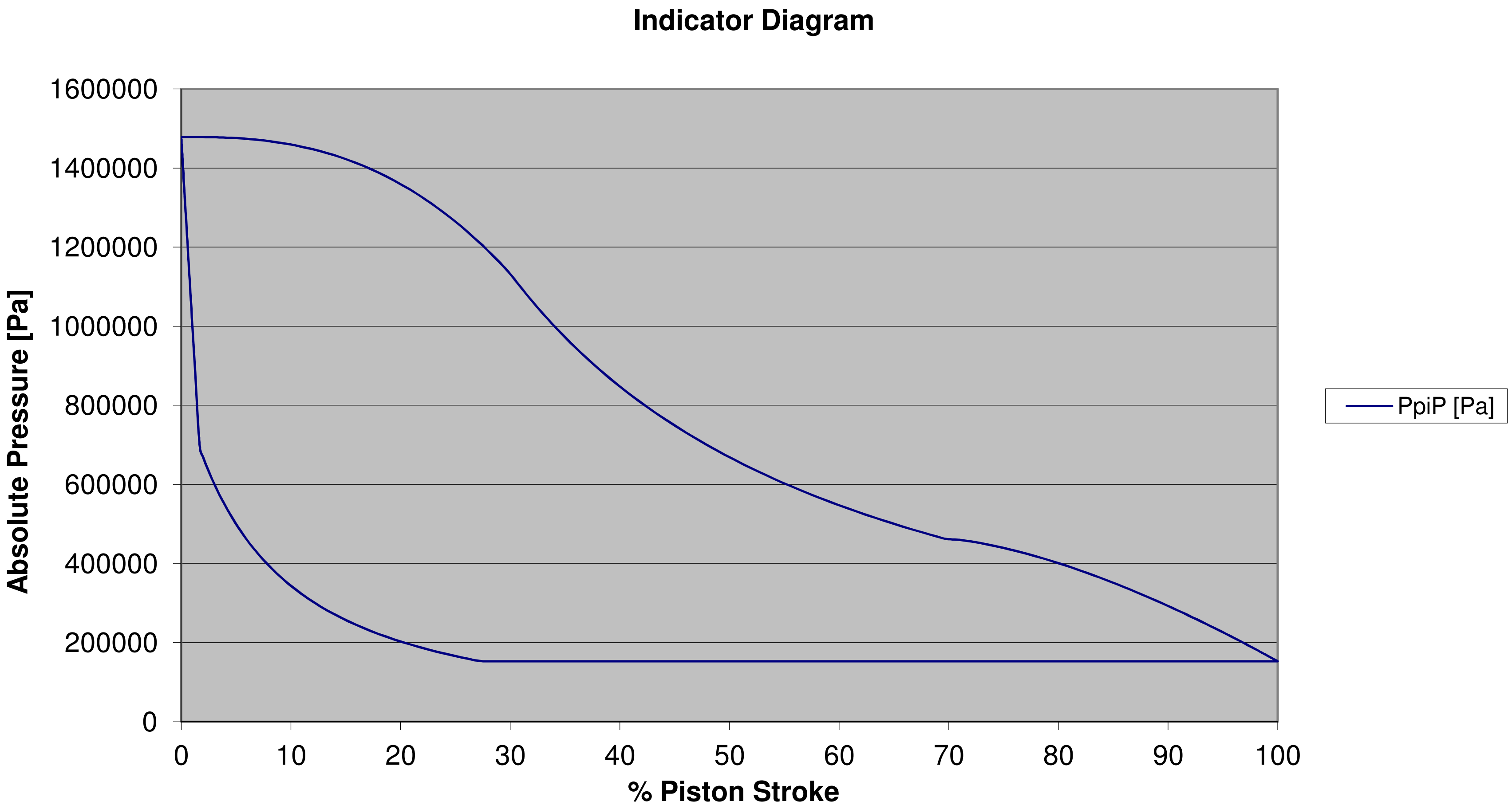
FEA Results

- Proof Load Case
  - 233 N/mm² (tensile)
  - 310 N/mm² (compressive)
- Material Yield 585 N/mm²
- Material UTS 775 N/mm²
- Reserve Factor: 1.9 (yield) 2.5 (UTS)

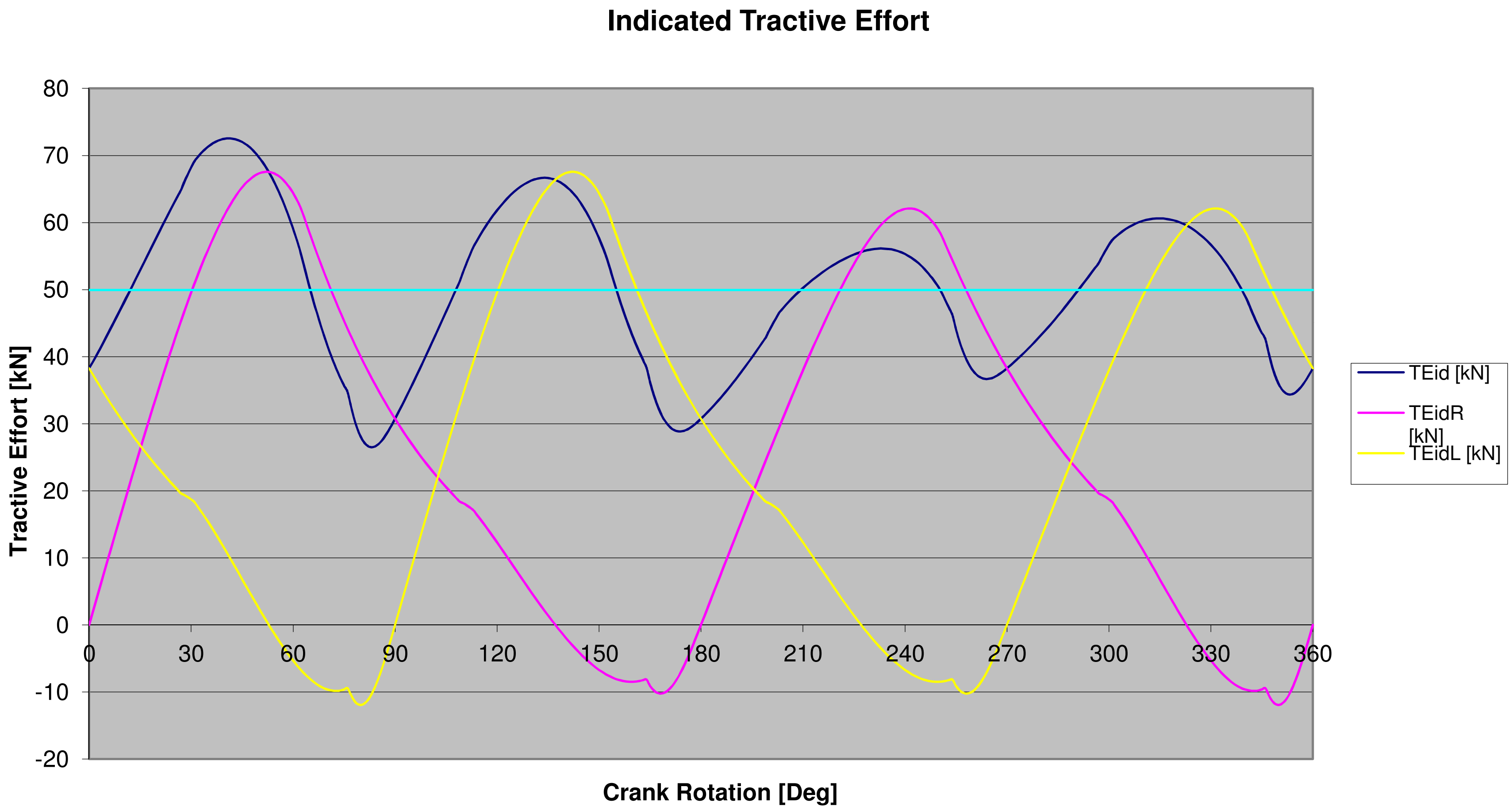
Fatigue Method 1

- Each type of loading assessed individually
  - Track forces: +/- 25g vert, +/- 5g lateral
- 15k miles per year
  - A) 1% mileage @ 90 mph, 25% cut off
  - B) 40% mileage @ 75 mph, 30% cut off
  - C) 59% mileage @ 50 mph, 50% cut off
- 50% drive on rear axle, 95% boiler pressure
- Fatigue damage summed using BS7608 as a guide.
- Four key locations on the rod assessed.
- Sufficient for 5 years between NDT

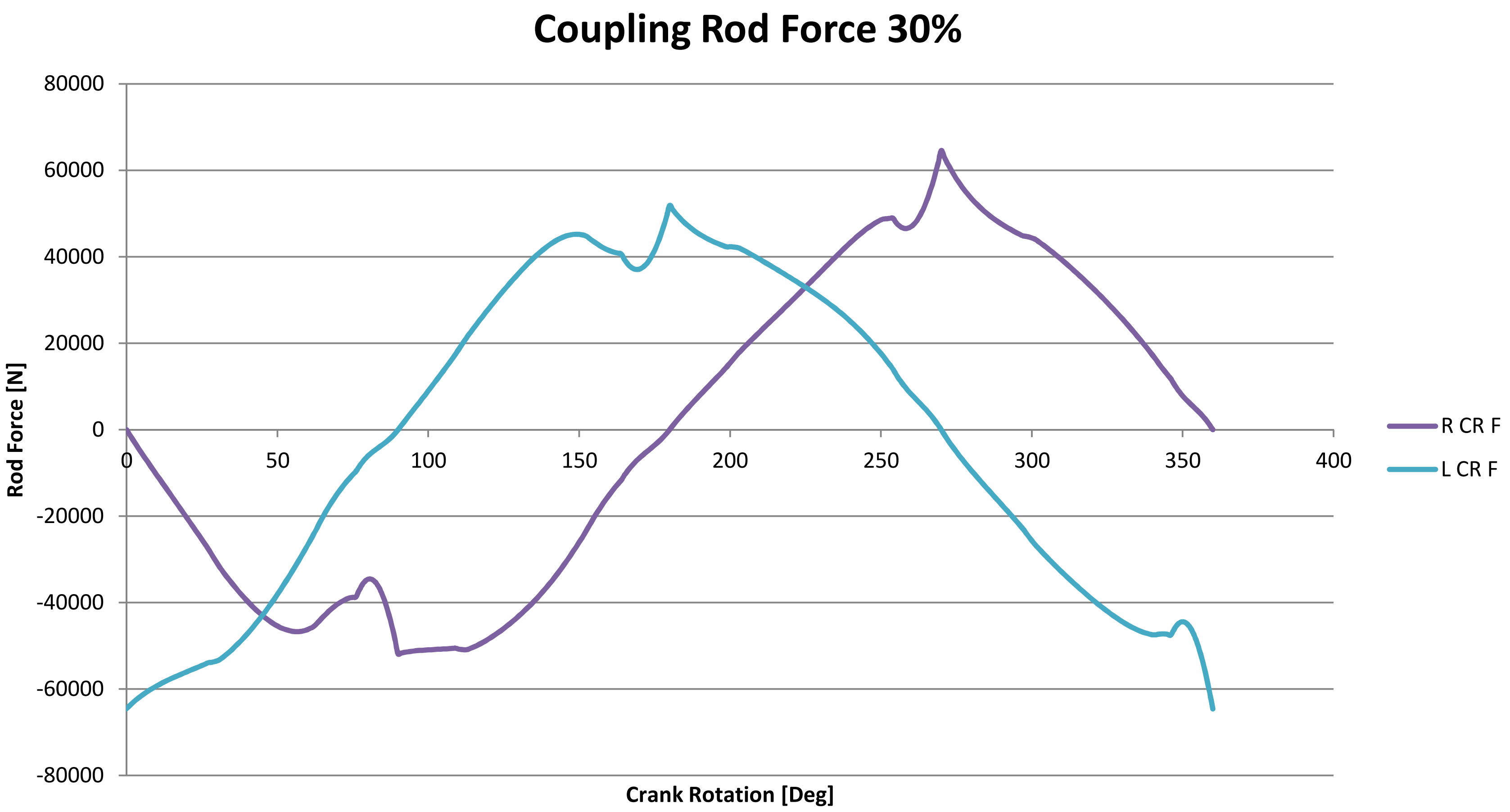
Complications!



More Complications



Yet more……



Coupling Rod Force 30%
80000
60000
40000
20000
0
-20000
-40000
-60000
-80000
Rod Force [N]
0
50
100
150
200
250
300
350
400
Crank Rotation [Deg]
R CR F
L CR F

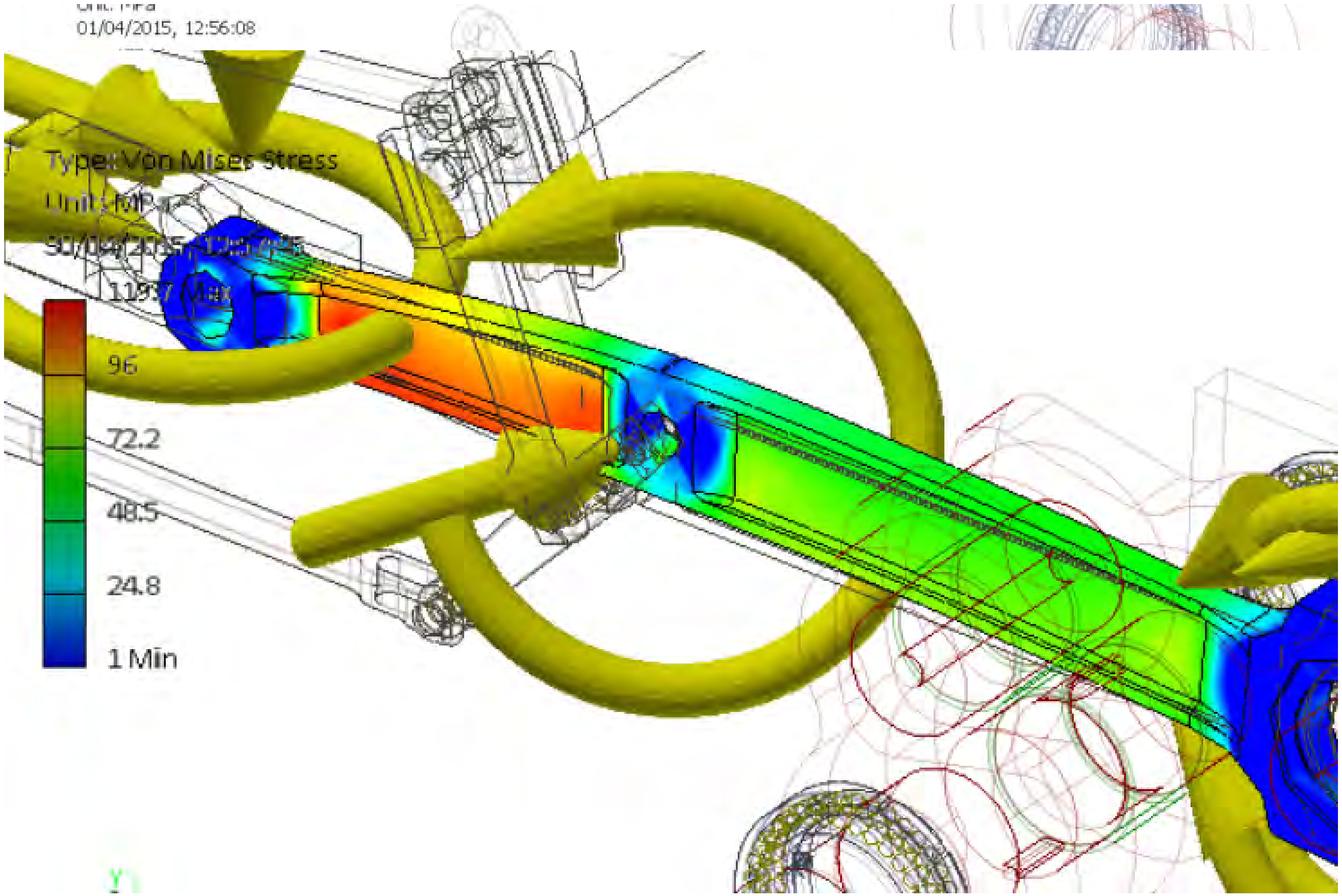
Fatigue Method 2 - Comparison

- Original rod – no reported failures in service:
  - Higher mileage
  - Lower quality material
  - Higher nominal stress
  - Poor NDT method (whitewash and hammer!)
- New rod:
  - Limited mileage
  - Better material
  - Lower nominal stress
  - Better NDT (MPI)

Conclusions

- Original rod close to buckling limit
- Re-design gives superior performance
  - No weight penalty
  - Near identical appearance
- Modern analytical tools
  - FEA
  - STEAM spreadsheet
- Result – a Coupling Rod fit for the Modern Railway

Coming Up Next.....



Thanks to Graham Shirley for images