HTS Roebel Cable strand alignment within cables and during coil winding

Dr Nick Long, Robinson Research Institute,
Victoria University of Wellington, New Zealand

WAMHTS-2, November 2014

Acknowledgements: Evgeny Talantsev, Rod Badcock, Chris Bumby, Zhenan Jiang, Wolfgang Nick (Siemens), Konstantinos Bouloukakis

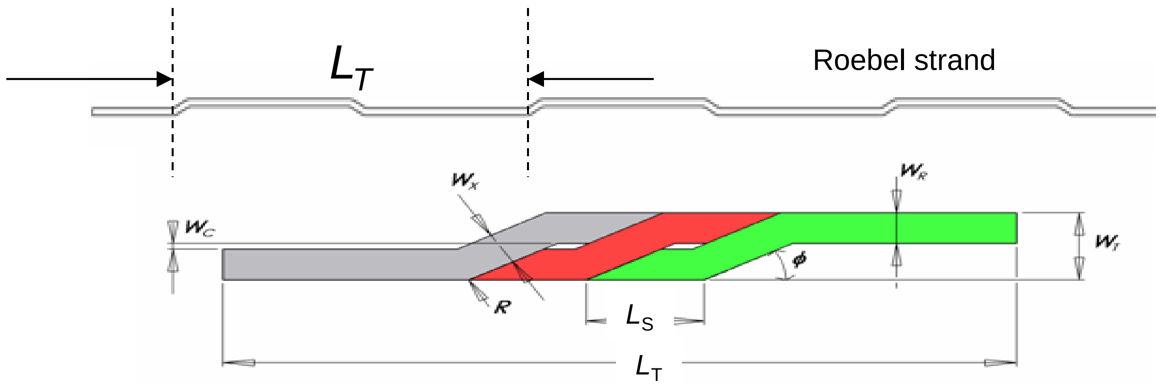
Contents

- Strand alignment in HTS Roebel cables
- Simple model: Effect of random error ΔL_T for strands
- Strand manufacturing process
- Results for individual transposition lengths
- Results averaged over longer strand lengths
- Cable assembly
- Coil winding
- Next steps
- Conclusions

HTS Roebel cable

Fundamental issue

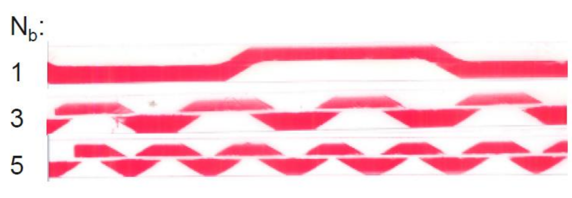
- Geometry of strands is fixed before cable and coil assembly



Strands wound together and geometric parameters

- For a fixed architecture (N, L_T, W_x, ϕ) there is an absolute minimum L_S (strand-strand spacing), this is point at which strands mechanically contact
- A higher practical minimum L_S may be set by behaviour with transverse stress

Recall Fleiter et al, WAMHTS-1



TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

Simple random error model

- Assume $(L_T)_i = \bar{L}_T + \Delta x_i$
- Cumulative error $(\Delta X)^2 = n(\Delta x)^2 = (\frac{L}{L_T})(\Delta x)^2$ n= # of transpositions
- Maximum length of cable that can be wound

$$L_{max} = L_T \left(\frac{\Delta X_c}{\Delta x}\right)^2$$

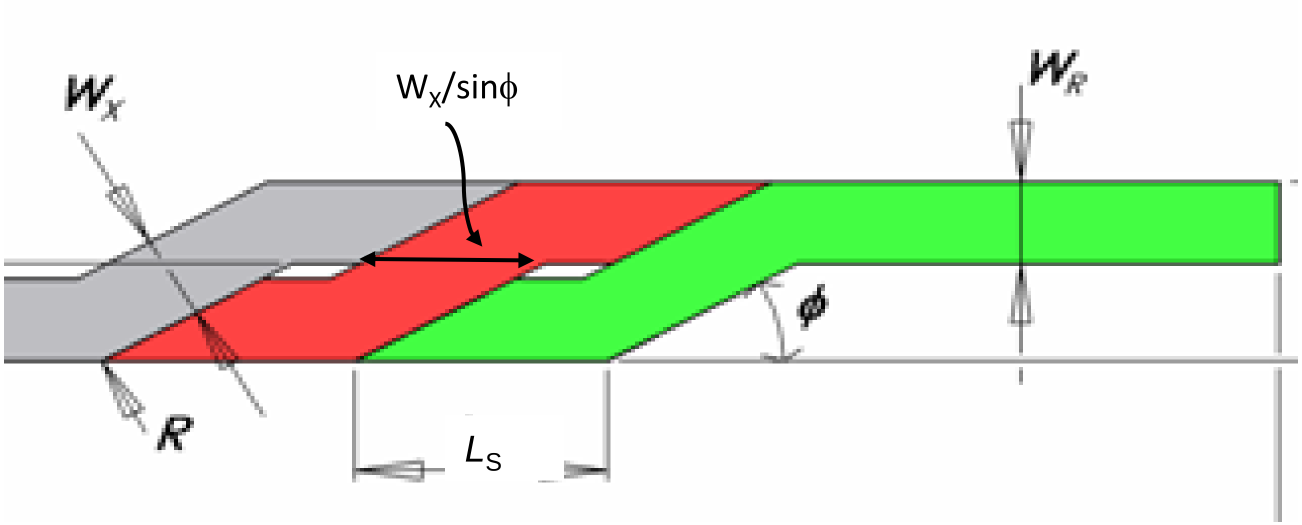
- Maximum cumulative error

$$\Delta X_c = \frac{L_S - (L_S)_{min}}{2}$$

$L_s = L_T/N$, designed spacing

- Need to estimate $(L_S)_{min}$

Geometry…



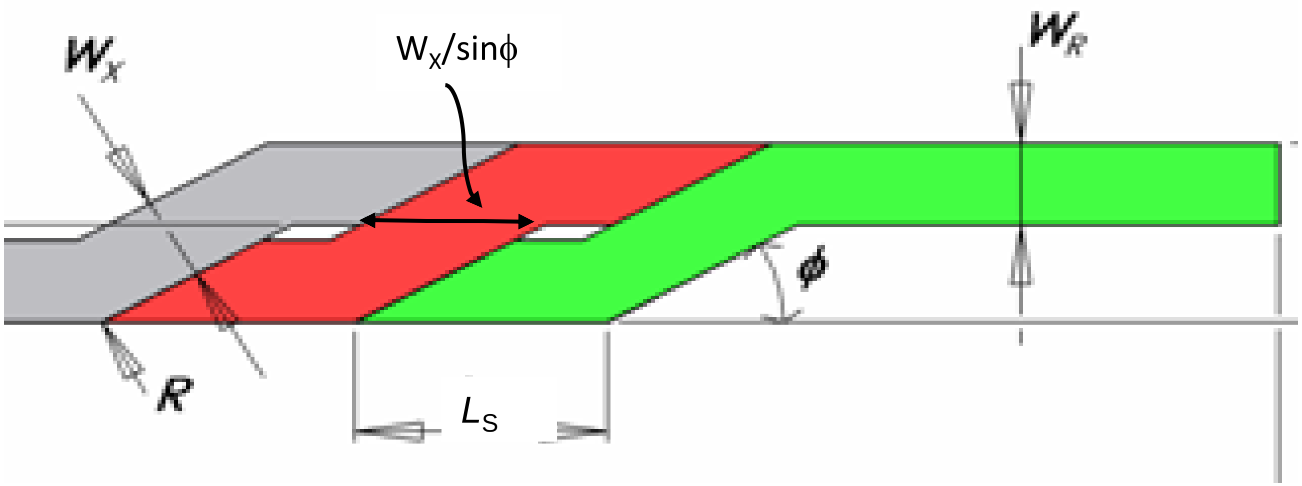
$(L_S)_{min} = W_X/\sin\phi$

For 15/5 cable with L_T = 300 mm
L_S = 20 mm
Absolute $(L_S)_{min}$ = 12.0 mm
ΔX_c= 4.00 mm,

E.g. Δx = 1 mm (0.3% of L_T)
L_{max} = 0.3 * 4^2 = 4.8 m

Δx = 100 μm (0.03%)
L_{max} = 0.3 * 40^2 = 480 m

Geometry…



$(L_S)_{min} = W_X/\sin\phi$

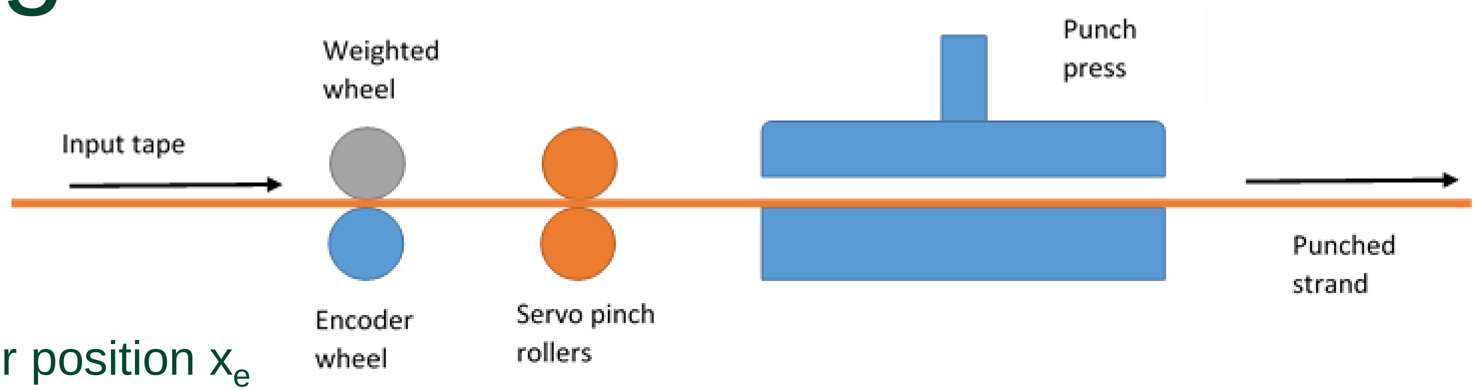
For 15/5 cable with L_T = 300 mm
L_S = 20 mm
Absolute $(L_S)_{min}$ = 12.0 mm
ΔX_c= 4.00 mm,

E.g. Δx = 1 mm (0.3% of L_T)
L_{max} = 0.3 * 4^2 = 4.8 m

Δx = 100 μm (0.03%)
L_{max} = 0.3 * 40^2 = 480 m

Systematic strand-strand error is much more problematic
$\Delta X_c = n * \Delta x_c$

Length control

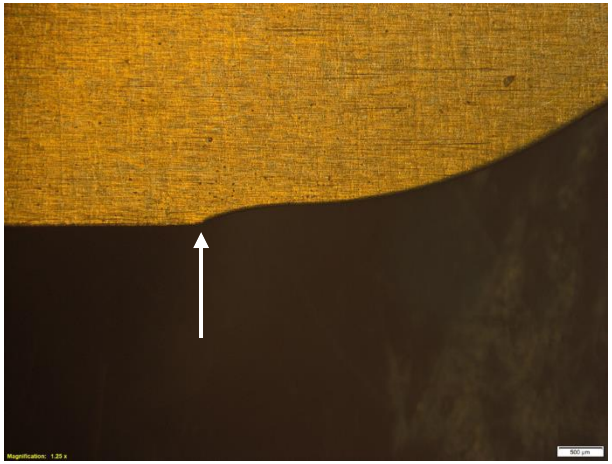


- Encoder position x_e
- Roller position x_r
- Rollers have a PID control – can undershoot or overshoot target position (can't go backwards)
- Algorithm
  - Calculate error $E_e=(x_e-x_{0e}) - nL_T$
  - Feed (full speed) $0.9L_T - E_e$
  - Calculate error $E_e=(x_e-x_{0e}) -(n+0.9)L_T$
  - Feed (half speed) $0.1L_T - E_e$
  - Punch
- Assumed trade off between speed and accuracy of each $(L_T)_i$
- Algorithm continually corrects for previous errors

Measuring L_T

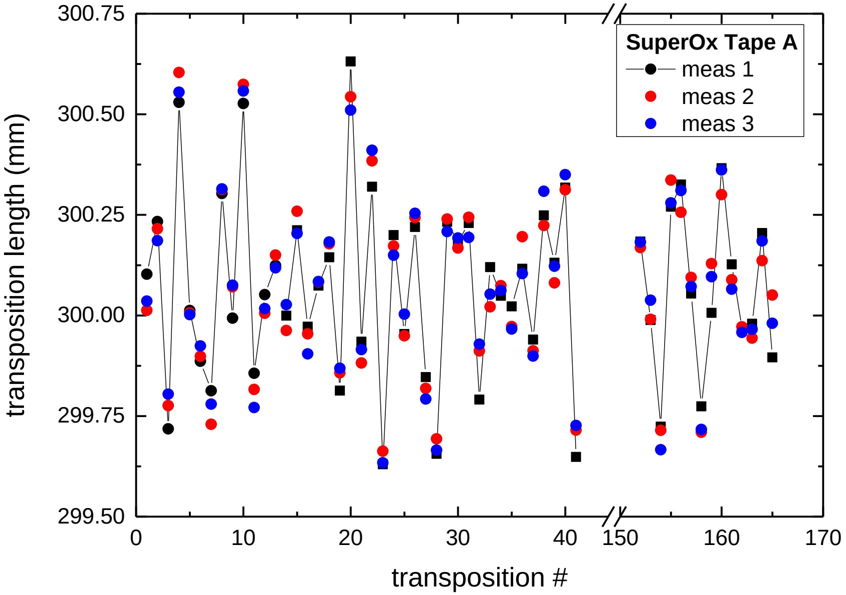
- Distance measured with laser interferometer on a 4 m bench
- Requires locating punching ‘defect’ in strand with microscope
- 10 N tension applied to strand

Length standards laboratory



Individual transpositions

- Any individual measurement has reproducibility of ~ 30 μm
- $(L_T)_{i+1} - (L_T)_i \sim 0.75$ mm (0.25%)
- Tend to get an oscillating structure to measurements
- Origin: feed roller or encoder or measurement error?



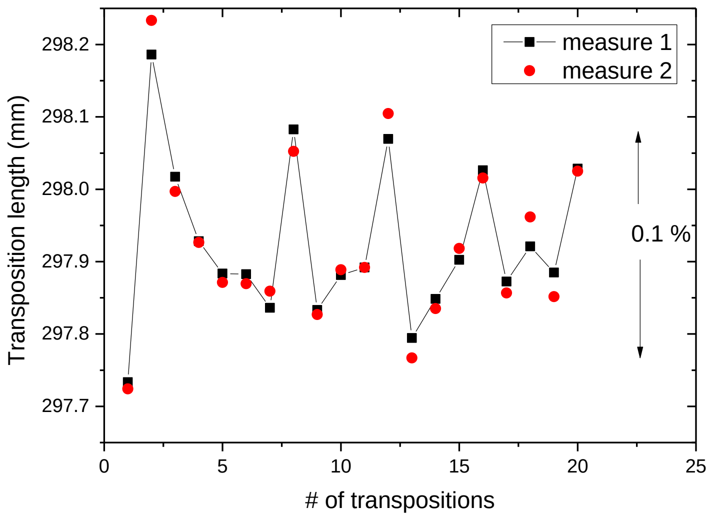
TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

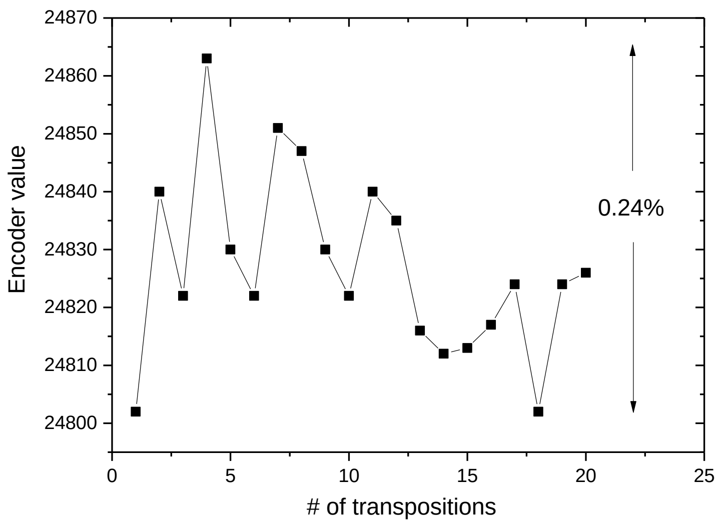
Experiment: Feed fixed roller increments and mark tape

- Length error is ~ 0.1%

Then check encoder values

- Encoder variation ~ 0.24%



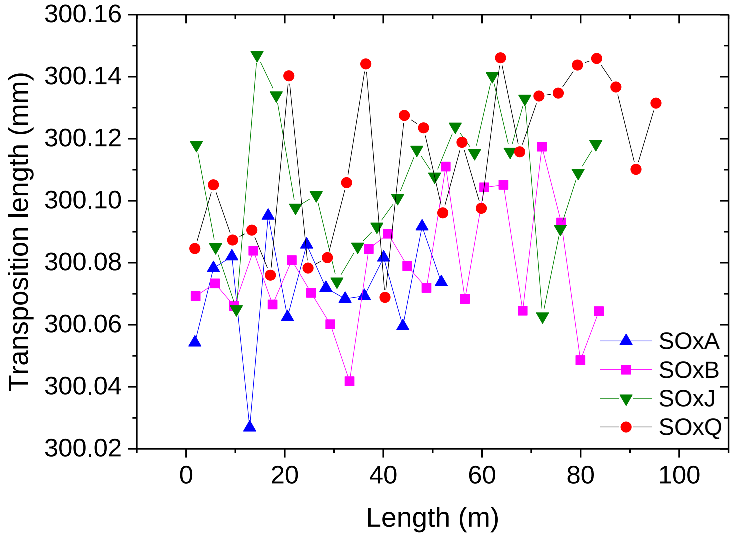


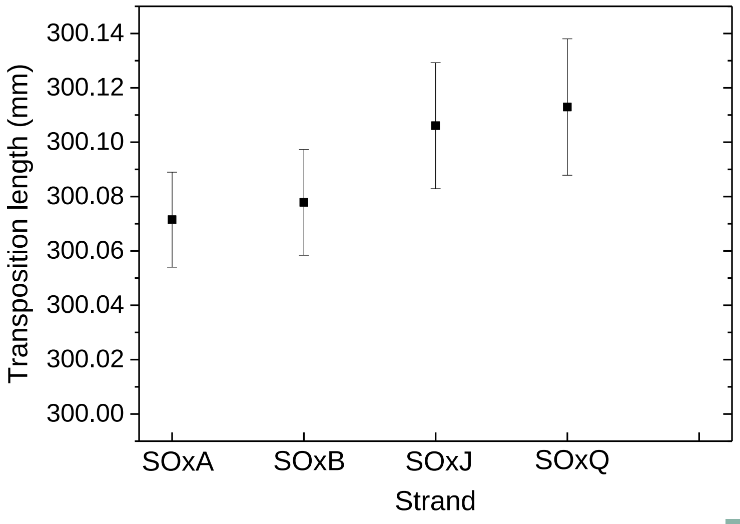
Conclusion: encoder less accurate than roll feeder
- May still have measurement error

Averaged transpositions (4 m)

- Punched SuperOx 'dummy' tape
- Much more consistent $\bar{L}_T$
- Results for up to 90 m length
- Overall random σ = 25 μm
- Some evidence for systematic errors between tapes Δx ~ 20 μm
- Systematic Δx ~ 20 μm limits cable length to $$L_{max} = L_T \frac{\Delta X_c}{\Delta x}$$

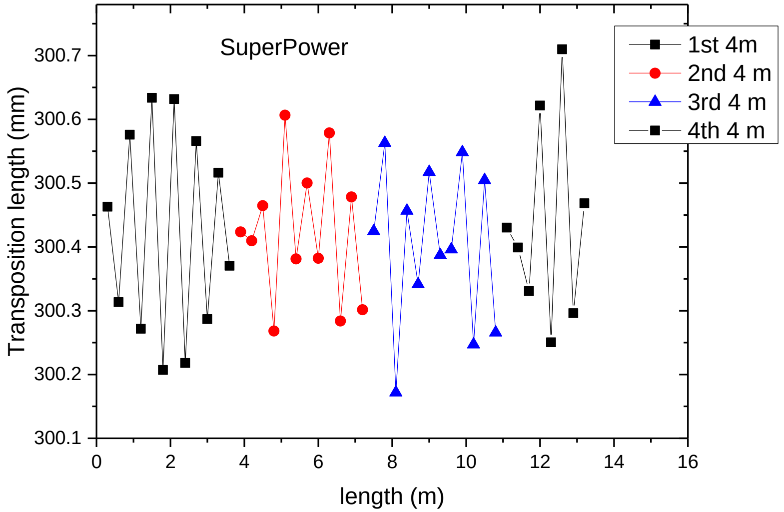
L_{max}= 0.3*4e-3/20e-6
= 60 m





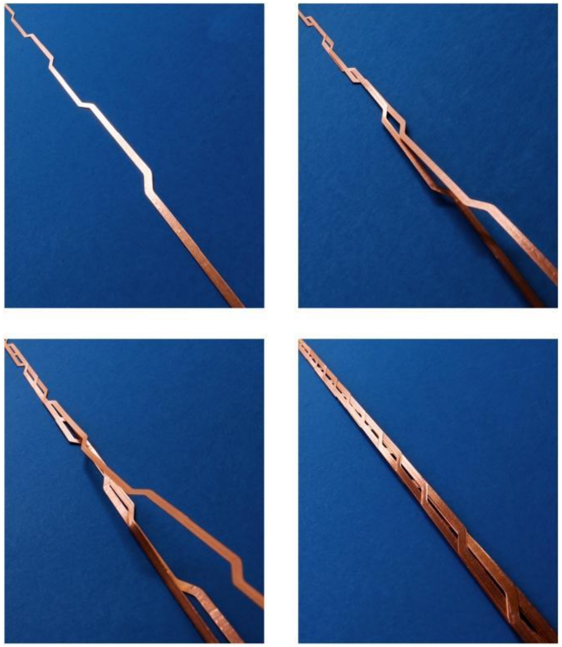
Conclusions on δL_T

- Adjacent transposition variations are large at present settings
- Averaged random errors are acceptable
- Systematic errors need more investigation
- No difference between tape manufacturers



Cable assembly

Illustration of the assembly process



Automated planetary wind system for 15/5 cable

Assembly issues

- How to set initial alignment of strands?
  - To date done ‘by eye’
  - Can we average over more than 1 transposition?
  - ‘By eye’ means error of +/- 1 mm
- Current assembly process uses low tension; tension of strands along cable axis is not constant during winding
  - Does this matter?
- Does a caterpillar take-up help strand alignment?
- Is a large diameter take up spool necessary? $d \gg L_T$

This is all work in progress!

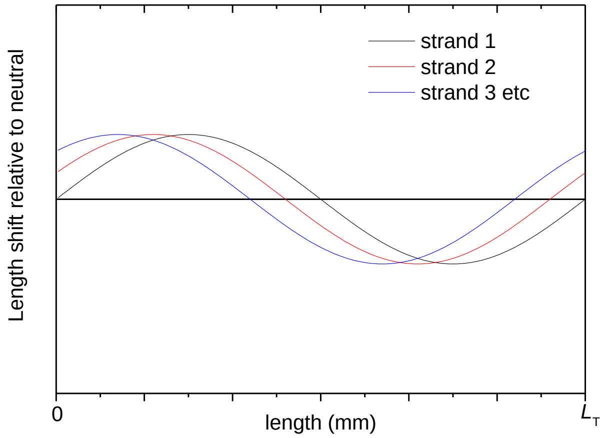
Winding coils

- Simplest case: solenoid coil
  - Strands equivalent; no relative shifts of position due to winding
- Racetrack
  - Relative strand positions shift around a curve
  - Model by W. Nick

$$\delta r = A\cos(\frac{2\pi x}{L})$$

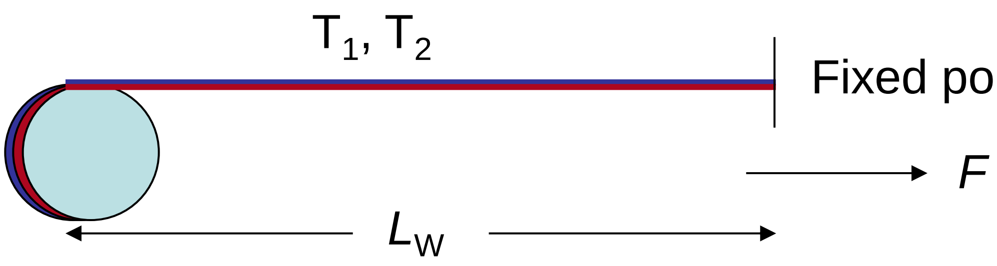
Position of strand relative to neutral axis of cable

$$\delta L = A\frac{\pi}{2}\frac{\sin X}{X}, X = \frac{\pi^2 R}{2L}$$



  - E.g. for 15/5, corner radius, 90°, R = 100 mm, maximum shift is δL = 0.4 mm
  - Question is how this shift is accommodated…
  - Also, how it adds to other errors…

Winding coils (cont)…



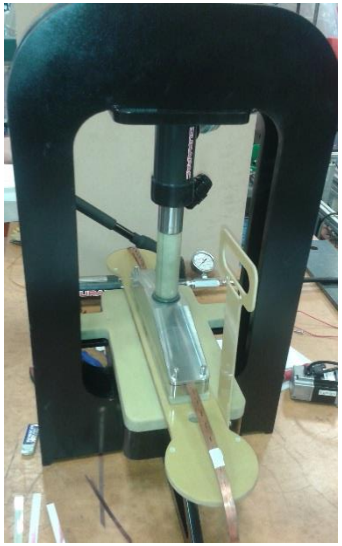
- Imagine 2-strand cable, wind on by π
- Δl = d * π (d ~ cable thickness)
- Now $T_1 \neq T_2$
- Apply force, F, to ensure strands in tension
- Implies a minimum L_W (to keep higher strain below ε_{irr})

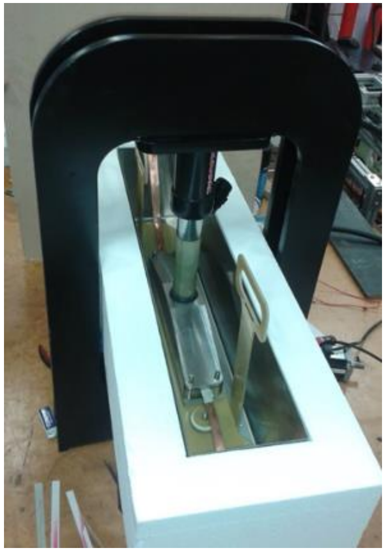
Roebel coil results

- RRI transformer solenoid
  - Successful I_c retention
  - 15/5 cable, 220 N winding force, not potted, single turn, Young's modulus E=31.3 Gpa
  - Drum pay-off
- Siemens small racetracks
  - Successful I_c retention
  - 7/5 reinforced cable, potted, 6-10 turns, similar Young's modulus
  - Caterpillar pay-off

Further work

- What is a more realistic limit of ΔX_c?
  - transverse stress testing of bare and potted cable
  - In-situ I_c measurement





Work in progress!

Further work

- L_T variations
  - Improve encoder mechanics
- Cable assembly
  - Testing of caterpillar
  - Long length alignment
- Coil winding
  - Can strand shift be accommodated by geometry choices?

TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

Conclusions

- Data for ΔL_T shows random and systematic errors
  - No issues for short length cables
  - Systematic errors require investigation – will limit length
- Work on assembly issues is in progress
- Coil winding creates strand shifts which can be modelled
- Understanding ΔX_c issues is in progress through pressure – I_c measurements

TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

Thank you for your attention!