North Auckland and Northland 220kV Cable Project – Managing Thermo-Mechanical Forces in Large Conductor XLPE Cable Circuits

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ABSTRACT

The North Auckland and Northland (NAaN) cable project is one of the most interesting and technically challenging long length land cable routes in the world, involving a major bridge crossing, a shared long length deep tunnel and buried duct routes, which pass through the centre of a major city.

The Utility recognised that sound thermo-mechanical design is an essential foundation for in-service reliability of large conductor 220kV 2500mm^2 XLPE cable systems.

Contractors were required to measure cable mechanical parameters and demonstrate the strength of cable system components and then validate the thermo-mechanical designs with FEA simulation techniques.

KEYWORDS

Auckland, NAaN, thermo-mechanical forces, XLPE cable, duct, tunnel, bridge crossing, rigid section, flexible section, transition section, locking wave, mechanical parameters.

INTRODUCTION

Auckland, the largest city in New Zealand, is almost completely surrounded by water. The City, coloured in grey in Figure 1, occupies a narrow isthmus between the Manukau Harbour on the Tasman Sea to the southwest and the Waitemata Harbour on the Pacific Ocean to the east.

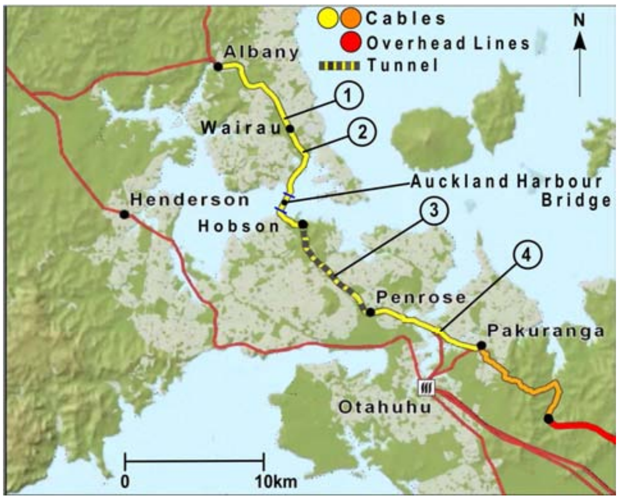

Fig. 1: NAaN project completes the Auckland ring

The central business district (CBD), item 3, lies adjacent to the Hobson Substation and is separated from the Northshore area of Auckland, items 2 and 1, by the Waitemata harbour. This is crossed by the Auckland Harbour Bridge (AHB), which carries a major motorway.

The NAaN cable project comprises the yellow section in Figure 1. The 36.5km long cable route is challenging for the management of cable thermo-mechanical forces. It involves large conductor sizes (Table 1), duct and tunnel sections, major bridge crossings and earthquake design requirements.

Table 1. Installation Sections and Cable Types

Installation Section			Cable Types		
N^o	Type	L km	Conductor mm^2	Sheath	Type*
1	Duct	8.4	2500	CAS	1 X
2a	Duct	5.9	2500	CAS	1 X
2b	Bridge	1.35	1600	APL	2 X
2c	Duct	2.4	2500	CAS	1 X
3	Tunnel	9.4	2500	APL	3 Y
4	Duct	9	2500	CAS	4 Y
Total:		36.5			
CAS: welded corrugated aluminium sheath					
APL: aluminium plastic laminate sheath					
* cable suppliers: X and Y					

Transpower required the largest current rating for the cable circuits reasonably achievable. Table 2 gives the power and current ratings by Section. 2500mm^2 enamelled copper conductors were specified for the in-ground Sections 1, 2a, 2c and 4 and deep tunnel Section 3. Section 2b on the Auckland Harbour Bridge was a complete drum length with no joints (1,350m) and as it was installed in air the smaller and lighter 1600mm^2 enamelled copper conductor achieved the same current rating.

Table 2: Continuously Loaded Winter Ratings

Section and Cable			Rating	
No	Type	Conductor mm^2	MVA	A
1	Duct	2500	602	1580
2a	Duct	2500	602	
2b	Bridge	1600		1580
2c	Duct	2500		
3	Tunnel	2500	781	2050
4	Duct	2500	735	1930

In 2001, Transpower and the local utilities started the development of a transmission corridor through the centre of the city, connecting Penrose Substation in the south to Albany Substation in the north. Together with an existing overhead line this would create a 220kV ring around Auckland City, Figure 1, and provide the opportunity for diverse supply routes to the major load centres.

A need was also identified to reinforce the transmission system into Auckland from the south. The North Island

Grid Upgrade Project (NIGU), involved the construction of a double circuit link from Whakamaru Substation (near the centre of the North Island hydro generating stations) to Pakuranga Substation (near the edge of the Auckland urban development).

NIGU comprised a double circuit overhead line, constructed for 400kV, but initially operating at 220kV. To avoid the environmental effects of an overhead line within the Auckland area, the final 11km was constructed using underground cables.

The Electricity Commission approved the NAaN project in 2009. This proposal now included a 9km underground cable link between Pakuranga and Penrose substations to provide a strong connection to the new NIGU circuits. The length of the NAaN and NIGU cable circuits is 47.5 km.

The new NAaN circuits had to use underground cables as the corridor was within the built environment of the city.

At the planning stage the transmission utility, Transpower, recognised the importance for reliability of thermo-mechanical forces and required they be evaluated and mitigated.

Fig. 2: Ducts installed under busway route

A key component of the tender documents was an obligation on the two cable contractors to calculate the thermo-mechanical forces that could occur in the cable and accessories. The cable contractors were required to design the cable installation to ensure that the calculated forces were less than the safe working limits. The calculations had to be based on known, or experimentally determined, cable mechanical properties and had to cover the complete range of installation conditions.

This paper describes the thermo-mechanical designs.

Fig. 3: Locking waves in a joint bay before backfill

SECTION 1 ALBANY TO WAIRAU: DUCTS

The installation of ducts along a motorway corridor permitted the cables in Sections 1 and 2 to be installed at a later date as a less disruptive operation. Installation approval from the transport agency was only possible as it was about to construct a busway adjacent to the motorway. It agreed that ducts for the future cables could be installed as part of the busway construction, Figure 2. Two banks of ducts were installed in trefoil and were embedded within a fluidised thermal backfill (FTB). There were route deviations across two motorway bridges. These duct sections were completed in 2008.

Cast in-situ joint bays were built. At each end of the joint bay where the cable emerged from the unfilled ducts the cable was rigidly constrained by the installation of locking waves, Figure 3, held in FTB.

Cable Duct-Span Simulation

Five of the duct spans were modelled in 2008 using a dynamic FEA simulation technique developed by EPRI for duct-manhole systems, [1],[2],[3], to i) confirm that the prospective cable designs would be within their design limits and ii) derive the forces necessary to design the joint bay constraint system. The values of the mechanical stiffness parameters EA, EI and GJ and the coefficient of friction μ were extrapolated from experimental measurements [1] on 138 kV 750 mm^2 and 220 kV 1250 mm^2 XLPE cables subject to rapid heating in ≤8 hours.

The contracts for cable supply had not been awarded and so the final cable constructions were unknown. Three possible 220kV 2500mm^2 cable constructions were modelled:

Cable A: SAS (welded, smooth, aluminium sheath).

Cable B: APL (aluminium foil, plastic, laminate).

Cable C: CAS (extruded, corrugated, aluminium sheath).

The NAaN duct had an internal diameter of 224mm and the cables had diametral clearances of 100.4mm, 97.1mm and 83.1mm respectively.

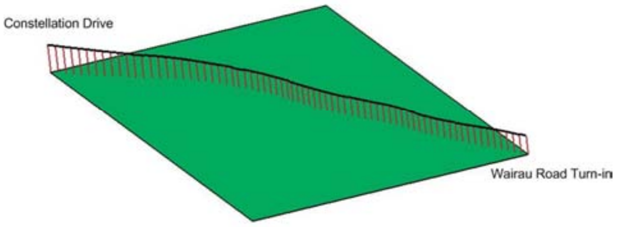

Fig. 4: 3D 'Stilt diagram' for FEA route simulation

The digital survey data for the 3.28km route, including five spans and four joint bays (JB), was input into the FEA model, Figure. 4

The model cable was heated from 15°C to 90°C. Figure 5 shows that thermo-mechanical patterns in Cable C were initiated at 45°C at points of natural route curvature (Figure 2) and by 90 °C they had occupied the majority of the span.

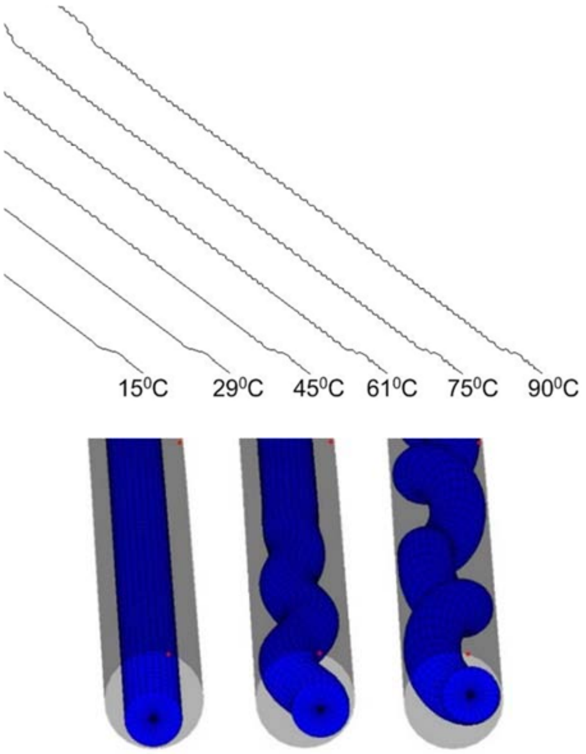

Fig. 5: thermo-mechanical patterns, JB 0-1
Left at 15°C Centre at 51°C Right at 90°C

The performances of the cables were confirmed to be satisfactory in not exceeding the limits of sheath strain, insulation sidewall pressure and minimum bending radius.

The forces acting at each of the four joint positions were output. Figure 6 is an example of the force distribution upon heating to 90°C in the first loading cycle. To design the cable constraint system in the joint bay it is necessary to know i) the value of maximum, absolute, axial force to prevent the cable buckling and ii) the maximum differential forces to prevent the XLPE core and joint moving lengthwise.

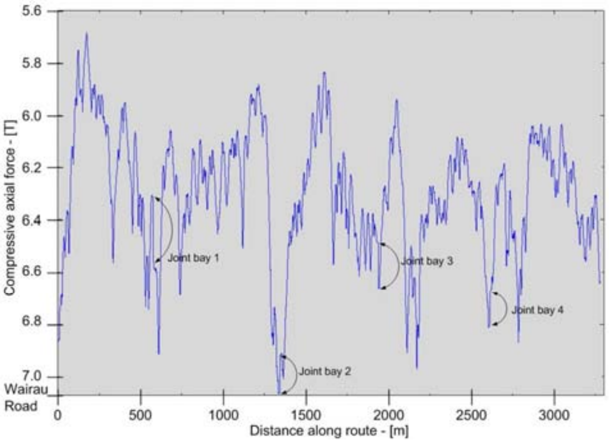

Fig. 6: Force along route on first heating to 90°C

The magnitude of the axial force is reduced by the formation of cable patterns, which absorb a proportion of the thermal expansion. The differential force results from differences in the cable patterns arising from route geometry variations on each side of the joint bay. The forces were obtained from simulations of different applied heating and cooling conditions. The maximum absolute compressive forces in the cables at the joints and the percentages of the maximum possible rigid bar force values were Cable A: 8.1t (51%), Cable C: 7.0t (44%) and Cable B: 3.7t (23%). The highest differential joint forces occurred after load-cycling and a cool-down to 5°C: Cable C: 2.4t, Cable B: 2.3t and Cable A: 1.9t. Suppliers demonstrated in later proving trials that their locking wave constraint designs could withstand a differential force of >3.5t.

Joint Bay Constraint System Models

The purpose of the constraint system is to eliminate risk of disturbance of the joint insulation. The joint bay chambers were to be back-filled. The simplest and most efficient method of constraining the cable is to form locking waves and hold them in FTB, as shown in Figure 3. Locking waves have the double benefit of preventing i) the extruded XLPE core sliding inside the metallic sheath and joint insulation and ii) the cable moving through the joint bay.

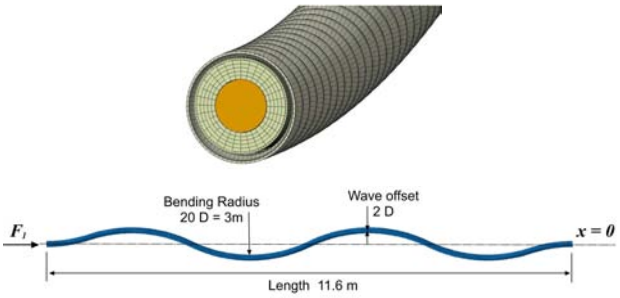

Fig. 7: FEA model of reference locking wave

An FEA sensitivity study was performed to provide a guide on the dimensions of locking waves needed to achieve a particular withstand force. A simulation was performed on a reference locking wave, Figure 7, in which the bending stiffness EI and axial stiffness EA of cable design C (CAS) were 3D modelled.

The study varied:

- Number of half-waves (and hence cumulative bend angle). Ref: 4 x half waves: 228 degrees.
- Amplitude of half waves. Ref: 2D = 299mm.
- Bend radius. Ref: 20D = 2.99m.
- Coefficient of friction between extruded core and sheath. Ref: 0.5
- Radial clearance core to sheath. Ref: 1 mm

Figure 8 shows the effect of varying the cumulative bend angle. The solid black line is from the FEA model of the 220 kV CAS cable. It represents the force that can be withstood before movement occurs without the need of a backing force at the low force end (i.e. the joint). The kink in the curve at the left hand end is where the geometry changes from a single half wave to a quarter wave (i.e. an ‘offset’). A 228o locking wave (four half waves) can withstand a 65kN compressive force. The FEA method is more relevant than simple capstan theory (broken lines), which takes the pessimistic case of cable having no bending stiffness e.g. the joint would be required to withstand a backing force of 9kN for the locking wave to withstand a thrust of 65kN for the same angle and coefficient of friction.

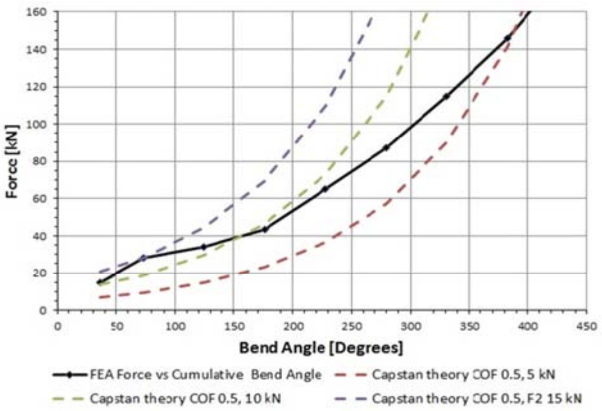

Fig. 8: Locking wave: force vs bend angle

The accompanying paper [4] reported that a locking wave comprising four half loops of CAS sheathed NAaN cable withstood an applied force of ±40kN requiring a minimal reaction force of <±1kN and exhibiting an end displacement of ≤1mm. Increased movement occurred at > 50 kN thrust. The sensitivity of withstand force to the coefficient of friction µ is nearly linear and so, in this case, the effective coefficient of friction µ lay between 0.3 - 0.5.

SECTION 2A (WAIRAU TO AHB NORTH ABUTMENT): DUCTS

Upon leaving Wairau Substation the cable ducts rejoined the east side of the busway and travelled southwards. The same ducted installation design as Section 1 was used.

A transition joint chamber was located above ground at the bridge north abutment to connect the 2500mm^2 CAS duct cable to the 1600mm^2 APL bridge cable.

SECTION 2B (AHB): FLEXIBLE

The 1.35 km continuous cable lengths were installed in trefoil formation and flexibly constrained in vertically sagged waves, Figure 9. The waves were designed to the formula in TB194 [5] with a span length of 3.75m and an offset of 250mm. A flexible installation reduces the loading on the bridge, is compatible with the flexible method of crossing the bridge expansion joints and is cost effective.

Fig. 9: Waved cables on Auckland Harbour Bridge

A thermo-mechanical ‘dilation span design’ was developed to permit the cables to cross the bridge’s central and end expansion joints and absorb both the horizontal movement of the bridge and the thermal expansion of the cable lengths in the spans. The design of the dilation, the proving trials and the in-service confirmatory measurements are detailed in an accompanying paper [4].

SECTION 2C (AHB SOUTH ABUTMENT TO HOBSON): DUCTS

A transition joint chamber was located at the bridge south abutment to connect the 1600mm^2 APL bridge cable to the 2500mm^2 CAS duct cable. The Section 1 ducted installation design was used.

Fig. 10: Pulling cable into ducts near CBD

The benefit of minimising traffic disruption in the approach to the CBD Hobson Street Substation was gained by pulling cable into the pre-laid ducts, Figure 10.

SECTION 3 (HOBSON - PENROSE) TUNNEL

The cable was terminated into GIS at Hobson Street Substation

Earthquake response calculations for the substation showed that, if the cables were to be rigidly cleated between the shaft head and the GIS terminations it would be possible for a differential vertical displacement to appear between the GIS and the cable. This was prevented by installing a flexible transition loop of large cumulative bend angle, Figure 11, between the GIS and the rigidly cleated cable in the shaft. The flexible loop is laid on, but not fixed to the floor.

Fig. 11: Flexible transition loop

The 220kV cable descends into an existing deep tunnel that had been constructed by the local distribution company to reinforce Auckland CBD. The new 220 kV NAaN cables and existing 110 kV XLPE cables share the tunnel. 33 kV and 22 kV cables are also present.

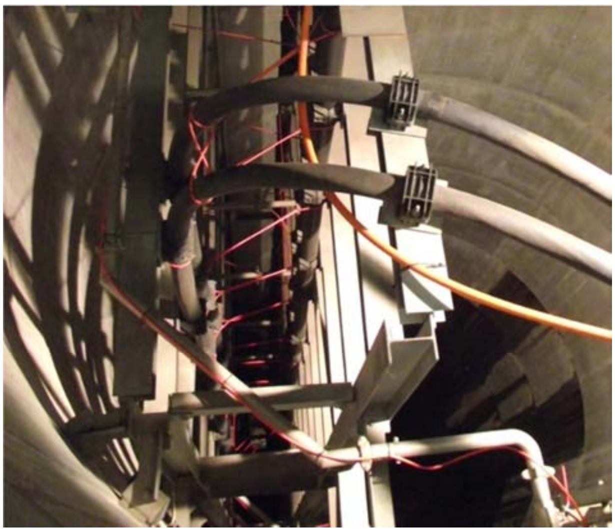

Fig. 12: 33 kV 3/C, 110kV S/C and rigidly cleated 220kV S/C cables descending Penrose shaft

Figure 12 shows 220kV and MV cables descending Penrose shaft on shared frames. The tunnel is 3m in diameter, 9.4km long and runs at 20m to 100m depth; predominantly below sea level. The shaft at Hobson Street is 15m deep and at Penrose Substation is 60m deep. In the tunnel the existing 110kV XLPE cables are in two trefoil groups installed in horizontal flexible waves, one on each wall, with supports at 2 m spacings.

The shafts and tunnel already had metalwork fixings in place. These predetermined i) that the 220 kV cable would be flexibly installed in the tunnel in a horizontal trefoil snaked formation and ii) the shaft cable would be rigidly constrained. The shaft cables are rigidly constrained in snaked formation with a wavelength of 4m and a peak to peak offset of 200mm. The tunnel cables are flexibly snaked with a wavelength of 8m and a peak to peak offset of 200mm. An FEA simulation showed the wave peaks have a 22mm travel.

Shaft Transition Section

At the base of the shaft a flexible transition system was installed to thermo-mechanically segregate the rigidly constrained shaft cable from the flexible horizontally snaked cable in the tunnel. The transition comprises an 8m long flexible half-wave constrained by horizontally sliding trefoil cleats having a maximum travel from 150 mm to 334 mm i.e. 184 mm. The loop was designed by the contractor to i) accommodate the residual thermal expansion from the rigidly cleated shaft cable, where it emerges from a 90° bend and ii) the thermal expansion from the length of cable in the transition loop. The merit of the flexible transition compared to a rigid locking wave transition is that it limits the loads on the support metalwork and tunnel walls.

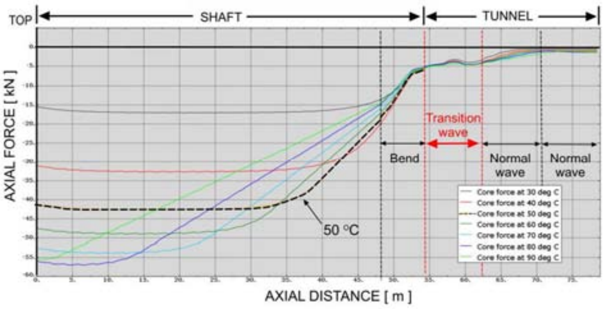

Fig. 13: Distribution of cable axial force down the shaft, around the bend and through the transition wave to the normal tunnel waves

A dynamic FEA simulation was performed, Figure 13, on a detailed model comprising the 54m shaft cables, the clamping cleat force, the rigid bend, the flexible transition section and the first two normal flexible waves in the tunnel.

Parameters derived from measurements on 220 kV 2500mm^2 APL cable were:

Max thrust: 5m length, 20^{o}C to 93.5^{o}C in 12 hours: 69 kN.
After 20 cycles: 48kN thrust, ≤23kN in tension.
EA: 58MN, based on $\alpha \approx 16.3.10^{-6}\,{}^oC^{-1}$, $\Delta\theta = 73.5^oC$.
EI: 16.9-17.3 kN.m^2 on a 2m length at ~20^{o}C, for R>50m.

The withstand strength of the APL clamp cleats and the pull-through strength of the cable core were measured. Figure 14 is a detail of the FEA output from the transition section showing the maximum 184 mm travel of the sliding cleats in their boxes from ambient temperature to 90^{o}C.

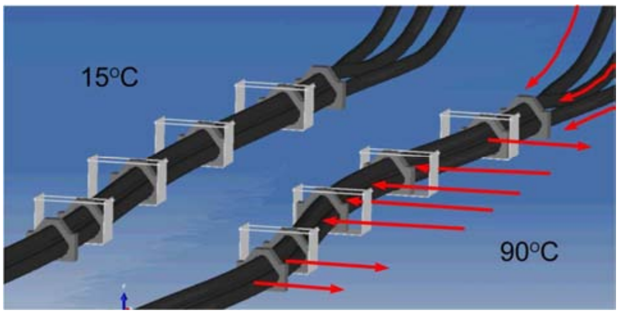

Fig: 14. Dynamic FEA of flexible transition section

Tunnel Joint Bay Transition Sections

Asymmetrical axial and transverse cable support loads unavoidably arise at the joint bays because of the need to position the joints in series for assembly.

Fig: 15. Tunnel joint bay during construction

Figure 15 shows the joints and cables before all of the clamp cleats had been fitted. The lengths of cable in the joint bay generate significant thermal expansion. The contractors installed flexible thermo-mechanical transition sections at each end of the joint bay to absorb the additional axial expansion and so ensure that the loads on the tunnel wall fixings were within their design limits.

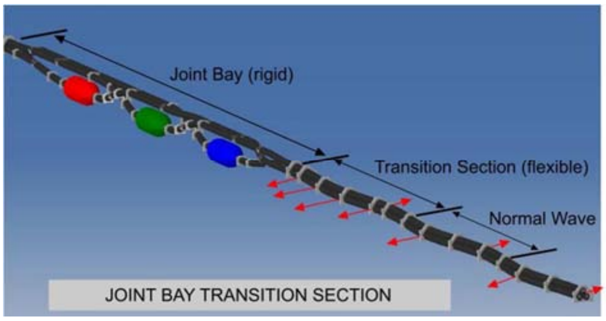

Fig. 16: Dynamic FEA of joint bay transition section

A dynamic FEA simulation was performed on a model of the joint bay, Figure 16, which included the flexible transition sections and two normal flexible waves to confirm i) the design and ii) that the differential axial loads across the joints were within their design limits.

SECTION 4 (PENROSE TO PAKURANGA): DUCTS

The cables in the 9 km route were installed in ducts in flat formation. Locking waves were installed at the joint bays. For motorway bridge crossings the cables left the ducts. The crossing of Pakuranga Creek was on a cable support structure connected to the bridge piers. The 528 m crossing of the Tamaki River was inside a concrete box girder. The cables were flexibly installed in horizontal snakes, with rotating node cleats and sliding brackets. Bridge expansion joints and sliding abutments were crossed using vertically sagged loops launched from radiused shoulders.

CONCLUSIONS

Transpower recognised that sound thermo-mechanical design is an essential foundation for in-service reliability of large conductor 220kV 2500mm^2 XLPE cable systems.

The requirement for contractors to measure the mechanical parameters of the cables, prove the strength of key system components and validate the thermo-mechanical designs with FEA simulation techniques was justified by results that differed from forecast values.

It is hoped that the information gained will be of benefit to future cable projects.

The final section of the NAaN cable project was commissioned and put into service in early 2014.

ACKNOWLEDGEMENTS

The Authors wish to thank Transpower New Zealand for permission to present this paper. The Authors acknowledge and thank all those who contributed to the success of the NAaN project viz. the Transpower Team of which Mr. McBurney was Project Manager and the main cable and installation contractors.

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