Report on Failed Cable Band Bolt Nuts
Forth Road Bridge

Forth Estuary Transport Authority
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Report on Failed Cable Band Bolt Nuts

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1 Introduction

In autumn 2007 whilst undertaking a check on tensions in cable band bolts, a cracked nut was discovered by FETA in one of the cable band bolts at PP54NW.

Further inspections carried out by FETA have revealed a further three nuts with cracks along the west cable. Inspection of the east cable has revealed another five cracked nuts. Appendix A shows the locations of all the failed nuts.

The Forth Road Bridge cable bands follow the traditional US style of being split vertically and stressed together using tensioned bolts, with a pair of wire rope hangers looped over the top. The number of bolts and the tension in them is determined so that there is sufficient resistance against slippage down the cable. In the main span most cable bands have 4 bolts and this increases to 6 bolts near the main towers where the cable is steepest. In the side span the number of bolts per cable band varies from 4 to 8 as the deck is heavier and the cable is inclined more steeply.

The original cable band bolts installed in the early 1960s during construction were made from high tensile steel and had a waisted shank. The nuts were of the “Roberts” pattern, turned down to a cylindrical cross section over part of their length to provide bearing on a shoulder.

Following partial failure of a hanger in 1995, a contract was let to Monberg & Thorsen to replace the hangers and also replace the cable band bolts in the cable bands with hangers. Design of new hangers and bolts was undertaken by WA Fairhurst. Bolt replacement was undertaken in 1999/2000.

FETA requested Faber Maunsell to investigate the failure mechanism and this report examines the four broken nuts from the west cable and discusses the various potential contributing factors. Part of the investigation included laboratory testing of the first bolt assembly.

2 Location and Characteristics of Failed Nuts

2.1 Details of broken nuts as found on the bridge (West Cable)

Photographs of all cracked nuts before replacement are shown below, with orientation diagrams:

1. 54NW

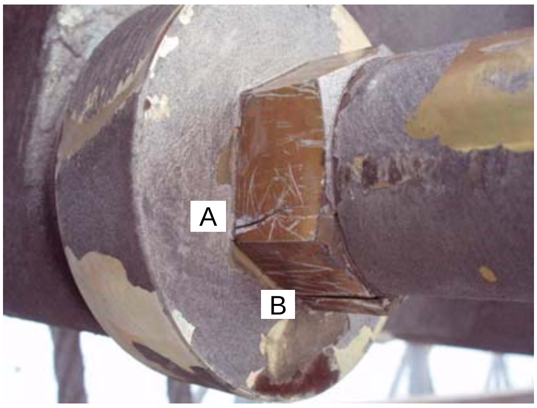


Fig 2.01: Cracks A & B

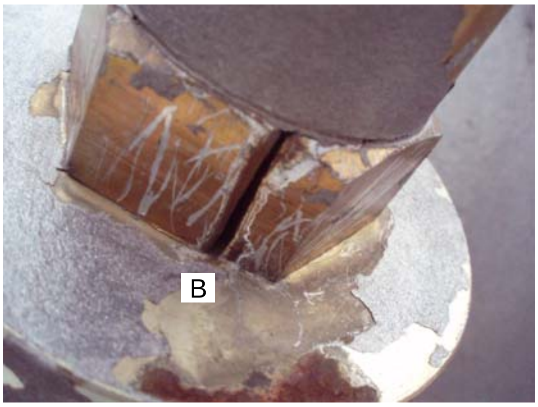


Fig 2.02: Crack B

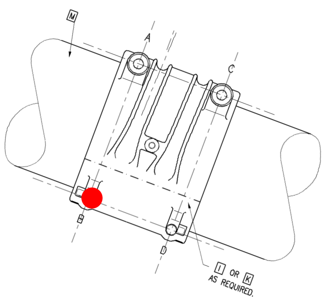


Fig 2.03: Location of failed nut on cable band

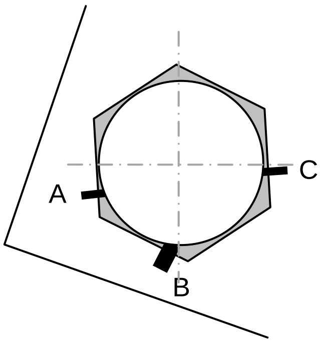


Fig 2.04: Location of cracks around nut

There was one wide crack approximately 2mm across (B), plus two narrower cracks on adjacent faces (A & C). The two narrow cracks appeared to taper in width from a maximum at the washer end to zero at the end cap face.

The failed nut was located at the live (jacking) end of the bolt.

2. 24SW

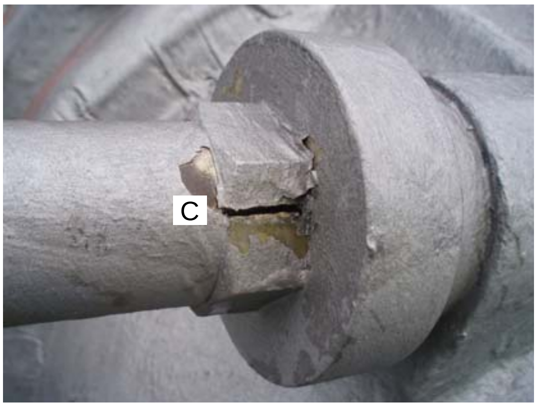


Fig 2.05: Crack C

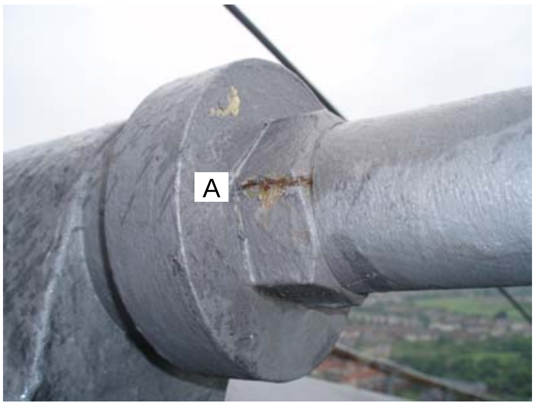


Fig 2.06: Crack A

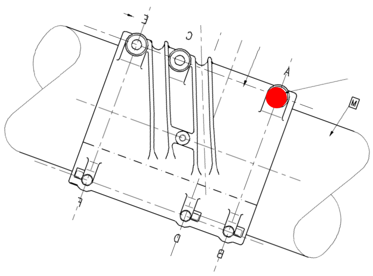


Fig 2.07: Location of failed nut on cable band

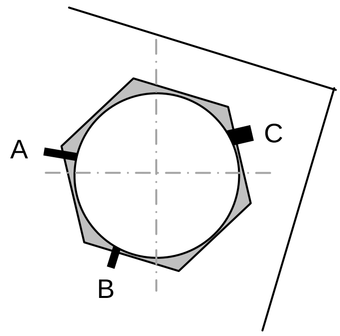


Fig 2.08: Location of cracks around nut

There was one wide crack (C), approximately 2mm wide, plus two narrower cracks, one of which was located on a corner of the nut hexagon (A).

The failed nut was located at the live (jacking) end of the bolt.

3. 42SW

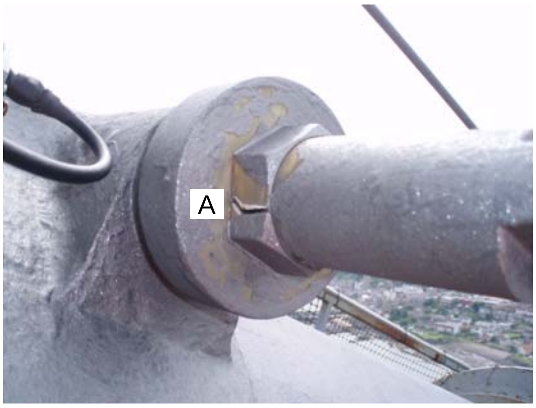


Fig 2.09: Crack A

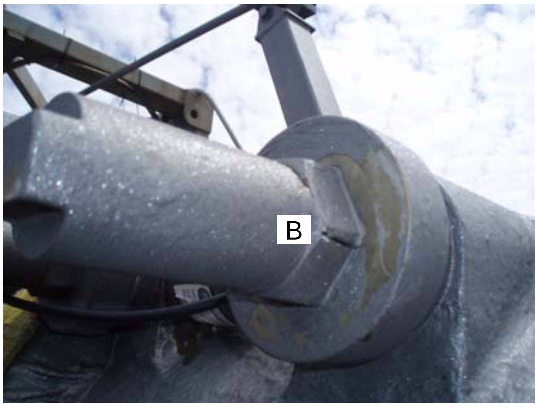
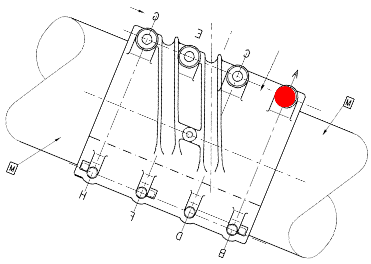


Fig 2.10: Crack B



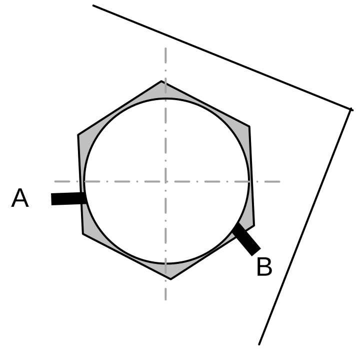


Fig 2.11: Location of failed nut on cable band

Fig 2.12: Location of cracks around nut

There were two cracks approximately 1.5mm wide running the full height of the exposed portion of the nut.

The failed nut was located at the live (jacking) end of the bolt.

4. 20NW

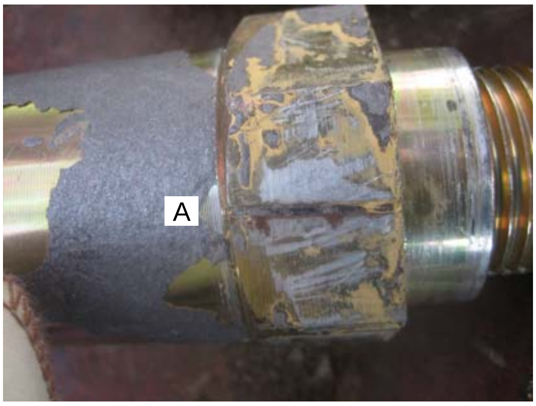
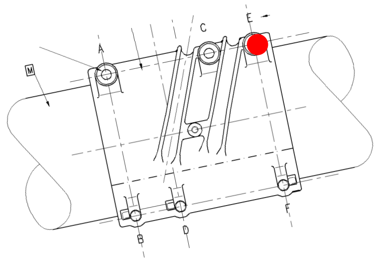


Fig 2.13: Crack A

Fig 2.14: Crack A on removal, note paint in crack



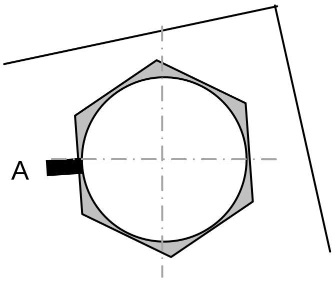


Fig 2.15: Location of failed nut on cable band

Fig 2.16: Location of cracks around nut

There was one single crack approximately 2mm wide in the centre of one of the nut hexagonal faces. There was evidence of perhaps two layers of paint inside in the crack.

The failed nut was located at the live (jacking) end of the bolt.

Other points of interest noted were as follows:

The end cap had been in close contact with the end of the nut suggesting that the end cap had been carrying a significant amount of the bolt tension.

Fig 2.17: Nut contact surface with end cap

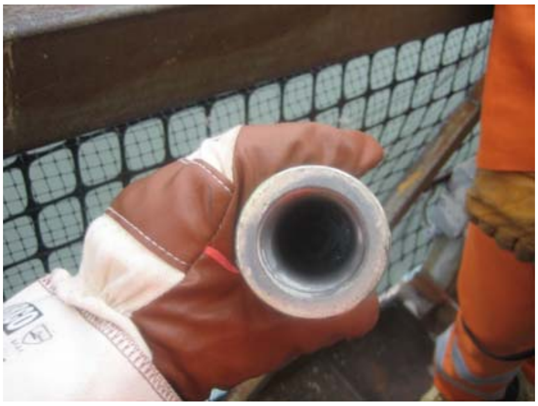


Fig 2.18: End cap

After removal and subsequent reassembly of the various parts, it was noted that the two halves of the spherical washers were not aligned concentrically with each other. In many ways this was not surprising as these heavy components would tend to slip down and rest on the bolt shaft before the bolt is tensioned.

Fig 2.19: Live end washers

Fig 2.20: Dead end washers

This effect is further illustrated in Figure 2.21 below for the live end. The larger convex washer can only drop a little as it is caught on the turned down section of the nut, but the smaller concave washer can slide around the spherical surface until it comes into contact with the threads of the bolt. The concave washer has a 46mm internal diameter, much larger than the 39mm bolt thread diameter. This allows a large angular adjustment in case the two faces of the cable band are not parallel, but if the set up is not carefully controlled on site and the cable band face the washer bears on is not cleaned properly, then an angular error could be introduced.

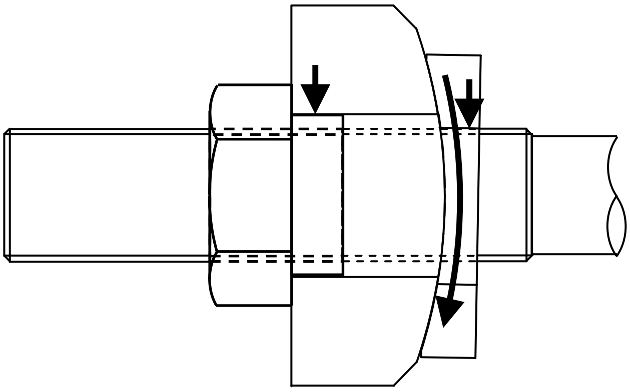


Fig 2.21: Slippage of live end washer under self weight

Summary of observations (west cable)

- The number of cracks on each nut varied from one to three.
- At least one of the cracks on each nut was very wide (2mm), suggesting the nuts had experienced a sudden release of hoop tension. It is suspected that friction on the washer face and the end cap maintained the open gaps until the bolt was removed, whereupon the gaps closed up.
- The crack in the damaged nut at 20NW had evidence of paint within the crack suggesting that failure had taken place between tensioning and painting (understood to be some six months later).
- The end caps are substantial and a proportion of the bolt tension was transferred to them after the nut had cracked. This appears fortuitous as it prevents total failure with components potentially dropping onto the carriageway and footway below.
- The heavy washer sets would tend to slump down under their own weight to rest on the bolt shank. This could lead to misalignment and eccentric loading of the nut if sufficient friction exists between the two washers.
- All failures were located on live side of tensioning system.
- All failures on the west cable were located on an outermost (corner) bolt.

2.2 Details of broken nuts as found on the bridge (East Cable)

Five broken nuts have been identified on the east cable, all located in the north side span. At the time of writing they are still insitu awaiting replacement when weather conditions improve and it is safe to access these locations. The following photographs taken during the inspection show the cracked nuts.

5. 18NE

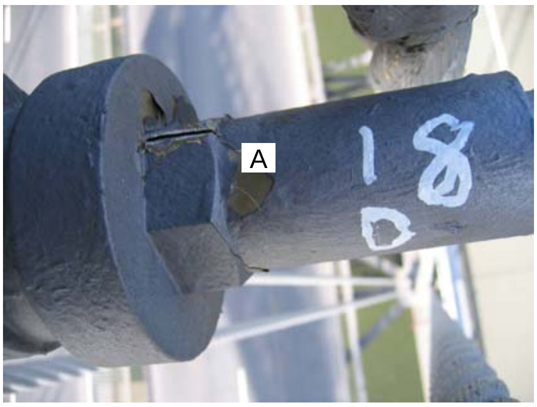


Fig 2.22: Crack A

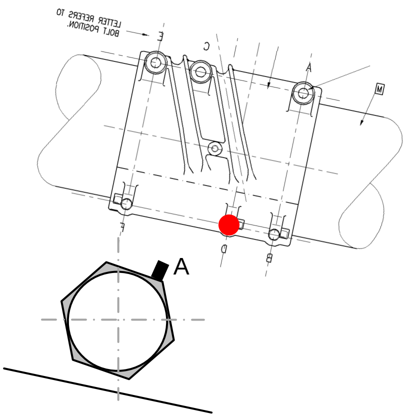


Fig 2.23: Location of nut and crack

6. 22NE

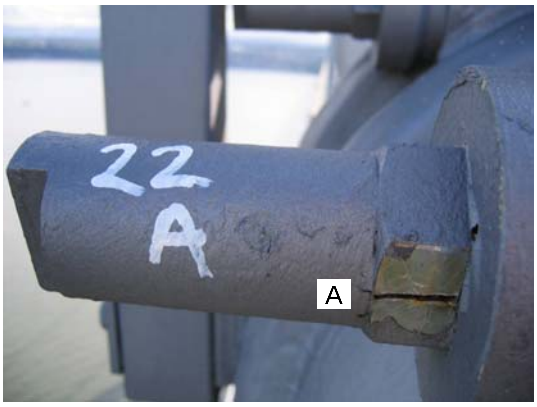


Fig 2.24: Crack A

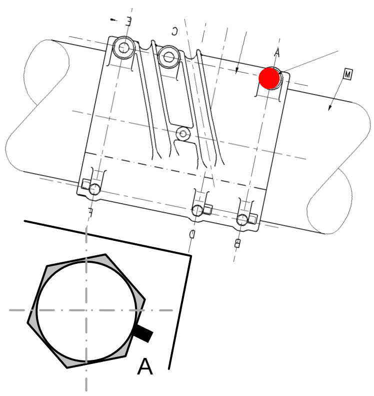


Fig 2.25: Location of nut and crack

7. 26NE

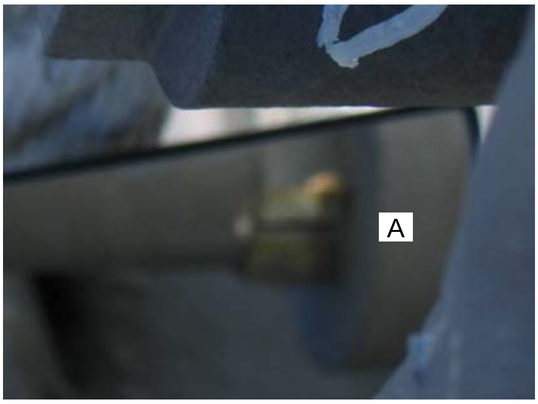


Fig 2.26: Crack A

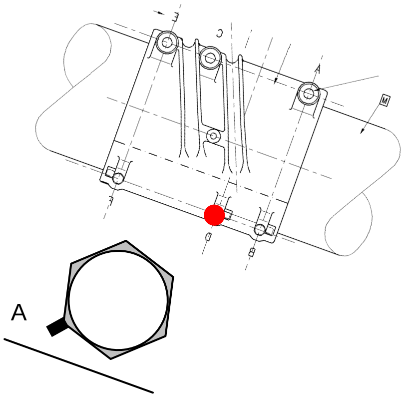


Fig 2.27: Location of nut and crack

8. 32NE

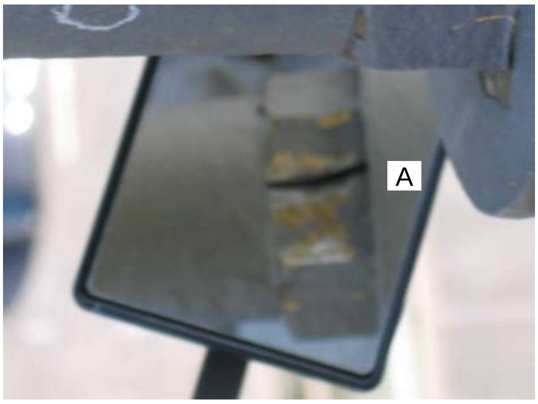


Fig 2.28: Crack A

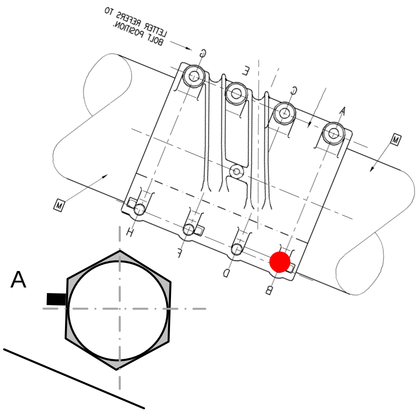


Fig 2.29: Location of nut and crack

9. 42NE

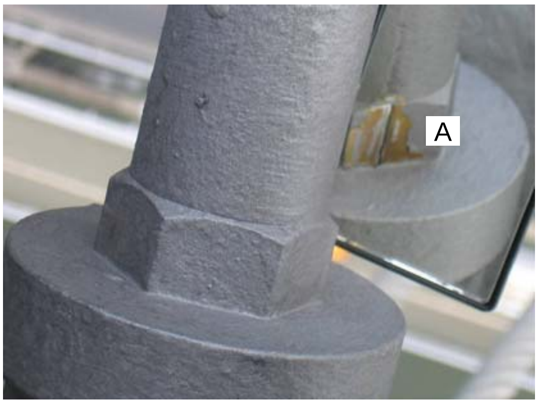


Fig 2.30: Crack A

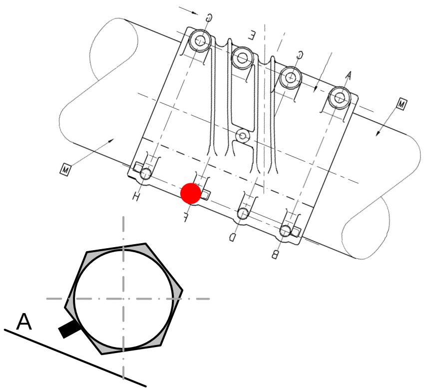


Fig 2.31: Location of nut and crack

Summary of observations (east cable)

- There appears to be a single crack in each nut
- All failures were located on the live side of the tensioning system.
- Only one failure was located on an outermost (corner) bolt, the other four were inner bolts.

2.3 Details of broken nuts after removal from bridge

1. 54NW

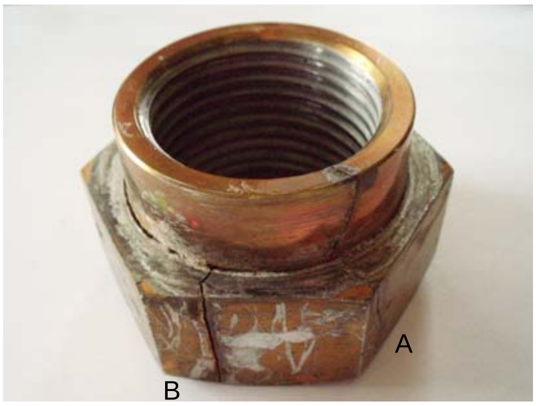


Fig 2.32: Cracks A and B

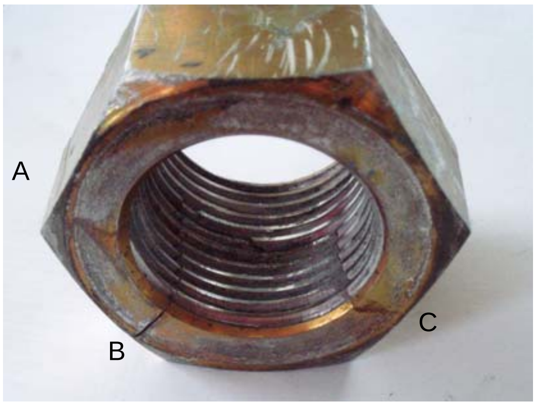


Fig 2.33: Cracks A, B and C

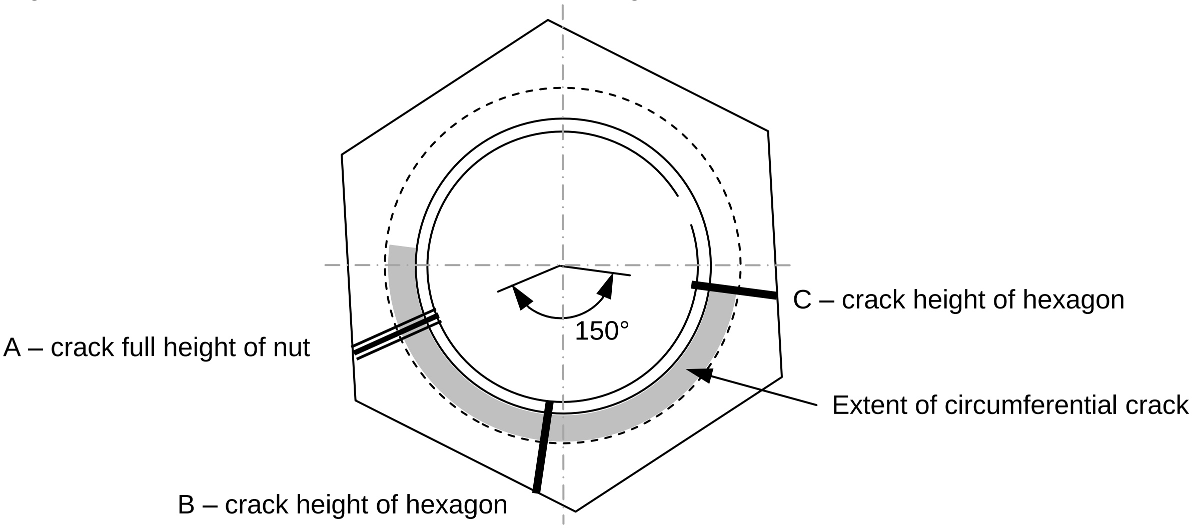


Fig 2.34: Plan layout of cracks

On removal, in spite of the large cracks the nut remained in one piece. This was a result of cracks A and C terminating just before the top of the hexagonal section and leaving a small amount of material in place. This nut was sent for laboratory analysis, where it was readily broken apart along the crack lines shown above. After splitting, a circumferential crack at the change in section was found to extend over an angle of approximately 150 degrees.

2. 24SW

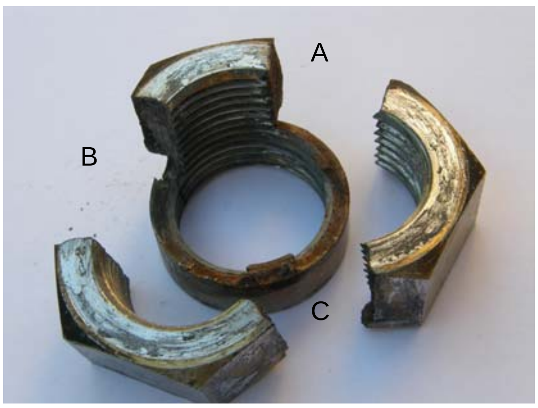


Fig 2.35: Cracks A, B and C

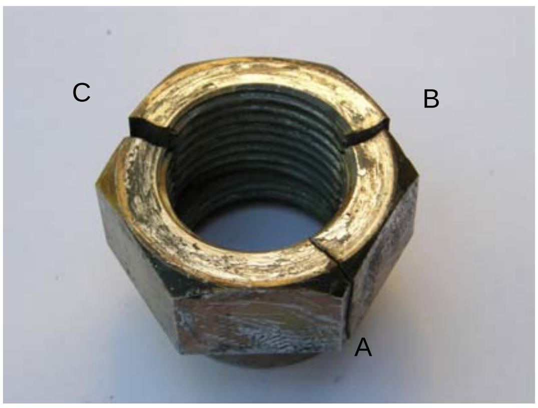


Fig 2.36: Cracks A, B and C

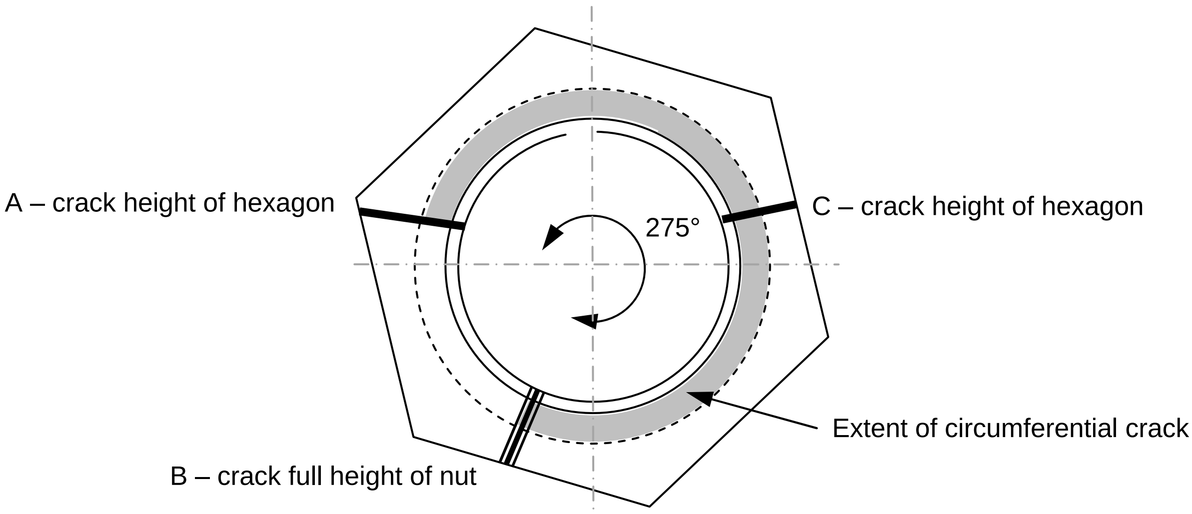


Fig 2.37: Plan layout of cracks

This nut also had three vertical cracks, two of which just extended over the height of the hexagon (A & C), and the third crack (B) was the full height of the nut. The nut split into three separate pieces, and at the change in section a circumferential crack was present over three quarters of the circumference.

3. 42SW

Fig 2.38: Crack B

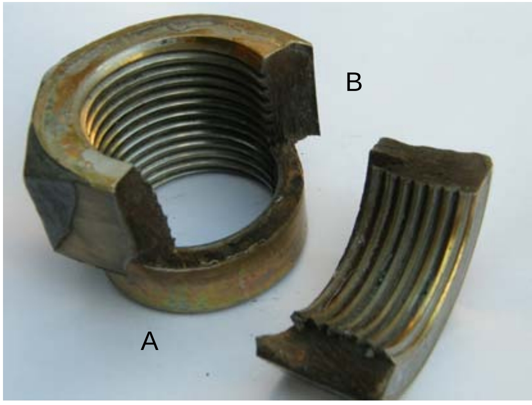


Fig 2.39: Cracks A and B

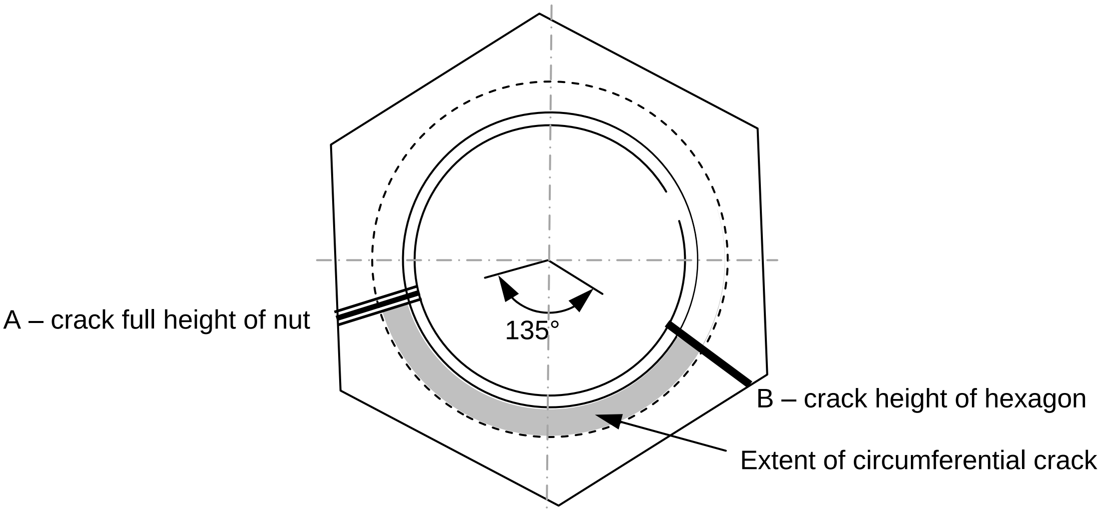


Fig 2.40: Plan layout of cracks

Two cracks were present, one full height and the other just over the height of the hexagon. The circumferential crack subtended an angle of about 135 degrees.

4. 20NW

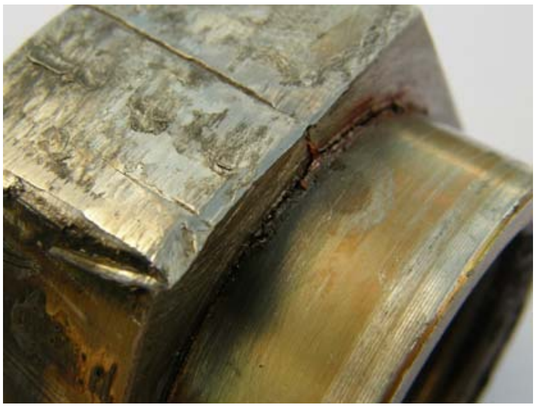


Fig 2.41: Crack A

Fig 2.42: Crack A

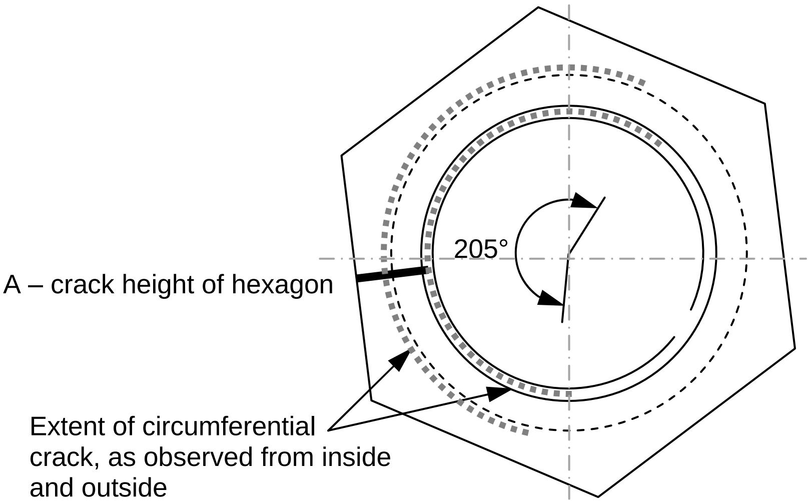


Fig 2.43: Plan layout of cracks

This nut was found to have just one crack and therefore remained in one piece. Careful examination at the change in section externally, and internally along the threads suggested the presence of a crack length of just over half of the circumference.

Summary

The number and extent of the cracks in the west cable nuts is set out in the table below.

Nut	Vertical Cracks			Circumferential Crack Extent
	Total	Full Height	Just in Hexagon	
1. 54NW	3	1	2	150°
2. 24SW	3	1	2	275°
3. 42SW	2	2	2	135°
4. 20NW	1	0	1	205°

Table 2.01: Summary of cracks in nuts from west cable

3 Laboratory Analysis

The entire assembly from the first failure was given to ESR Technology to carry out laboratory analysis. This included the bolt, the failed and un-failed nut, plus the two sets of washers. Their scope of work included the following:

- Visual examination
- Measurement of thread profiles and machined radius at change in section
- Dye penetrant testing to check for other cracks and defects
- Scanning Electron Microscope (SEM) examination of fracture surfaces to determine nature and type of cracking
- Metallurgical sections examined by optical microscope to identify presence of remote cracks, examine microstructure and characterise fracture surfaces
- Measurement of cadmium thickness and distribution
- Surface hardness measurements
- Chemical composition checks
- Tensile testing

The findings were as follows:

- Examination of the threads showed no gross deformation that could have caused the nut to lock. There was some deformation in the threads at the end of the threads where most load transfer was to be expected. The radius at the change in section was found to be about 0.3mm, slightly greater than the drawing specification of 0.25mm.
- The dye penetrant did not reveal any other major cracks.
- The SEM revealed that the transverse cracking had initiated from several locations (5 to 7) along the machined radius, and the fracture faces were primarily brittle fracture made up of several steps. The cadmium plating was either very thin or missing in patches around the machined radius. Where the cadmium plating was intact, it appeared to be dense. The longitudinal fractures were difficult to examine due to corrosion, but there were fibrous in texture and were the result of overload. There was no evidence of cracking mechanism such as corrosion fatigue.
- The metallurgical sections showed that the cadmium plate was generally uniform, but there were areas such as threads and the machined radius where it was missing. Generally the missing areas were as result of corrosion and sacrificial loss of the cadmium. In the failed nut, several corrosion pits in the underlying steel were found in the machined radius, and one was found to have a small secondary crack (see photo below).

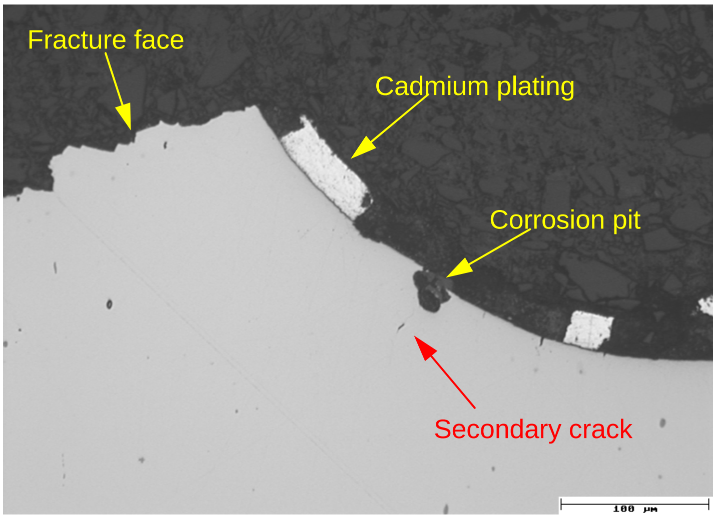


Fig 3.01: Metallurgical section at machined radius

The longitudinal fractures were all fibrous and ragged in appearance indicating the failure had been caused by an overload. The texture of the fracture faces suggested that they had propagated in a series of rapid steps.

The transverse fracture running around the machined radius consisted of several cracks that had propagated together. Several had initiated from corrosion pits where the cadmium plating was missing, having been consumed by the corrosion process. The shape of this fracture suggested that it was the oldest and slowest growing.

The underlying nut material was as expected banded (a result of the working direction during manufacture), the banding ran longitudinally along the nut axis. The steel was found to be in the bainitic phase, which is the preferred form for strong engineering steels. There was no evidence of any cracks away from the primary fractures.

As expected the steel contained numerous manganese sulphide inclusions, but there was no evidence of any gross inclusions or material defects such as oxides, silicates, slag, voids or porosity.

There was no evidence of any enlarged “blown” inclusions especially near the fracture face to suggest there was any hydrogen embrittlement.

Examination of the bolt showed that the cadmium plating was relatively uniform on the majority of the area, but some gaps were noted in areas such as thread tips. Here there was evidence of light corrosion only. The underlying bolt material was lightly banded, and the steel was bainitic with no evidence of cracks.

- The bolt had the most uniform thickness of cadmium plating, however, the failed and un-failed nuts were not so well protected. Several areas were devoid of cadmium and corrosion of steel had started. The failed nut had the largest missing areas and the corrosion pits tended to be deeper.
- Surface hardness measurements were taken using a Vickers indenter. Average hardnesses of 434, 418 and 428 HV10 were measured on the fractured nut, un-fractured nut and the bolt respectively. These correspond to tensile strengths of approximately 1426, 1364 and 1402 N/mm^2.
- Chemical analyses of the three components showed conformance with the specification for 826M40.
- A tensile test was undertaken using one sample taken from each component. The nut samples were “mini tensile” test samples due to the size of material available, and were taken parallel to the hexagonal faces. All results were above the limits set in BS 970.

The conclusions were as follows:

- The failed nut contained two types of fracture, a transverse crack leading around the machined radius at the change in section, and longitudinal cracks through the nut associated with the transverse crack.
- The transverse fracture consisted of several cracks that had propagated together. These tended to be tight cracks that had initiated from corrosion pits where the cadmium plating had become depleted. The shape of the fracture suggested that it was the oldest and the slowest growing. The majority of the fracture surface was brittle, most likely caused by a series of overloads.
- The transverse crack did not appear to be affected by the inclusions, and did not propagate from one inclusion to another. This indicates that there was no hydrogen embrittlement present, which might have arisen from the cadmium plating process.
- The longitudinal fractures were all fibrous and ragged in appearance indicating overload. The texture of the fracture faces suggested that they had propagated in a series of rapid steps.
- The nature of the cracking suggests that this will not be an isolated example. It is thought that many of the nuts will be at some stage of the failure process. The rate of deterioration appears to be governed by the formation of a corrosion pit and initiation of a crack. The amount of corrosion on the nut will depend on the local environment and protection given by the protective coatings.

- Due to design of the nut and washer assemblies it is not possible to visually inspect them insitu for presence of transverse cracks in the machined radius. These cracks could only be detected by NDT or metallurgical examination of a representative number of nuts.
- Generally the nut and bolt material was in a satisfactory condition. The nuts and bolts contained steel in the bainite phase, which is appropriate, and there was no evidence of other cracks. There were numerous manganese sulphide inclusions, but no evidence of gross inclusions or material defects.
- Chemical analysis and tensile testing confirmed that the material properties were within specification.

4 Roberts Bolts

The style of nut used in the original and replacement cable band bolts follows the Roberts Bolt developed by Sir Gilbert Roberts of Freeman Fox & Partners. It is helpful to understand how this bolt functions as it will provide an understanding of the behaviour of the cable band bolts.

The Roberts bolt was conceived for use on the Auckland Harbour Bridge. The transition from rivets was underway and grip bolts were just coming into use. These were ordinary high tensile bolts stressed to about 80% of their yield strength and breakages were not uncommon during tightening. Roberts realised that improvements to the bolt design could be made to eliminate this problem whilst providing certainty in achieving the required tension and enabling installation to be undertaken by relatively unskilled labour. The majority of cost in a bolted connection was the drilling of the holes and so a slightly more expensive bolt of higher strength would be economic. The first step was to use a waisted shank to move the most highly stressed area away from the threads. Early tests showed that when tensioned to beyond the yield stress in the shank, ordinary nuts seized and cracked, and the thin washers deformed. Specially shouldered nuts and thick washers of hardened steel were developed, which proved to be satisfactory. The Roberts bolt design used for connections on the Forth Road Bridge deck and towers is shown below.

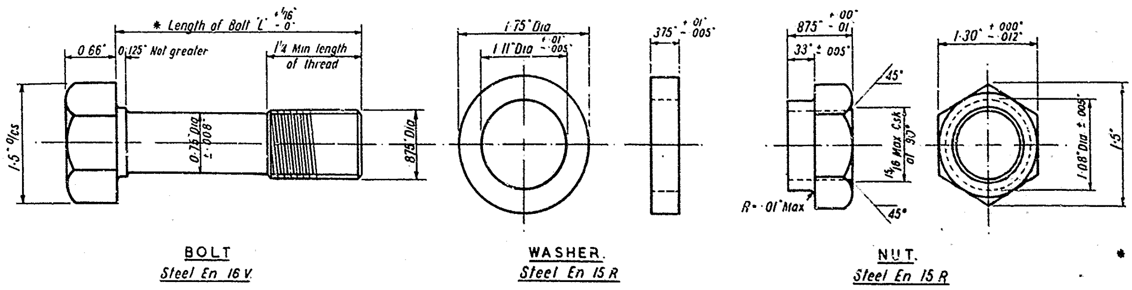


Fig 4.01: Roberts Bolt, as used on Forth Road Bridge (from drawing FRB 325)

The nut is essentially a standard 7/8 inch diameter BSF nut, lengthened by 1/8 inch and turned down at one end by 3/8 inch. In allowing the nut to bear on a thick washer, the load distribution along the threads is rendered more uniform and the possibility of thread stripping eliminated. Note the comprehensive set of tolerances to ensure the assembly functions correctly.

In order to achieve the maximum load possible in the bolt it is tensioned up to its ultimate strength. The graph below illustrates the load extension relationship for a typical 60mm grip length bolt. After applying a bedding load by hand, the nut is given a three quarter turn. It can be seen that maximum load is actually obtained after about a half turn following bedding down, but that a total of three turns is required for the bolt to fail. This enables the bolt to achieve maximum efficiency, whilst providing adequate safety through its ductility prior to fracture.

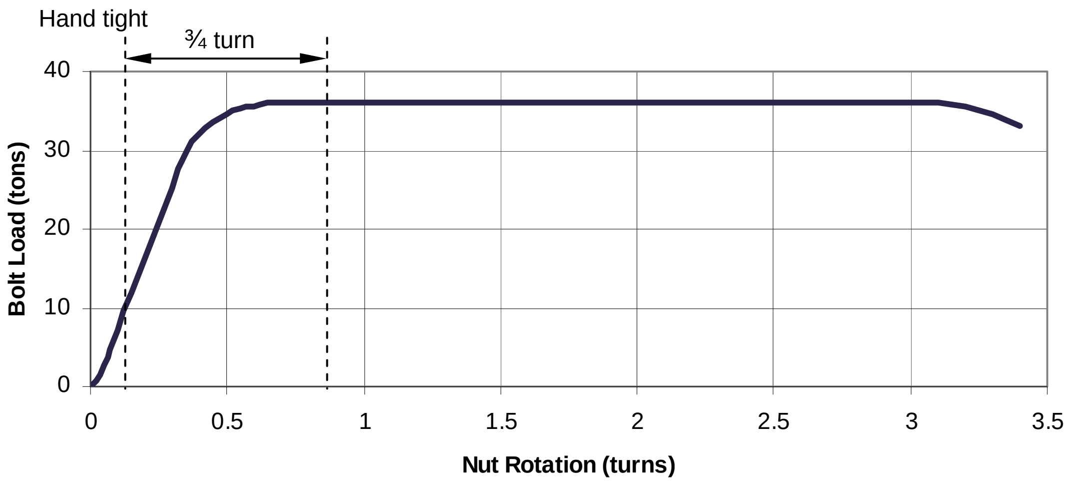


Fig 4.02: Load – extension curve for Roberts Bolt

The choice of material is important to ensure that the long plateau is available before the bolt fractures; hence ductility is a key requirement. The bolt is a “V” grade, with a tensile strength of 1000N/mm^2, and is matched with somewhat softer “R” grade washer and nut (TS 695N/mm^2).

The normal protective treatment applied to Roberts bolts was cadmium plating. There are a number of known instances of failure in service due to hydrogen embrittlement, which was attributed to poor control during manufacture. Generally failure was within the length of waisted shank.

The use of Roberts type nuts on cable band bolts is relatively limited. They are known to have been used on Severn (original and replacement), Humber, Bosporus 1 and 2, and Tsing Ma. Recent major European bridges (Storebaelt and Hoga Kusten) use waisted shank bolts and ordinary nuts. Recent US bridges (Carquinez and East Bay) use parallel shank headed bolts of medium strength (approx, Grade 8.8), resulting in the need for many more bolts and a much larger and heavier cable bands.

5 Salient Factors

This section of the report examines and discusses the various salient factors that could contribute to the nut failures.

5.1 Dimensions

A comparison of the dimensions of the nuts, bolts and washers has been made, as follows.

5.1.1 Bolts

Drawings of the original and replacement bolts are given in Figures 5.01 and 5.02 below.

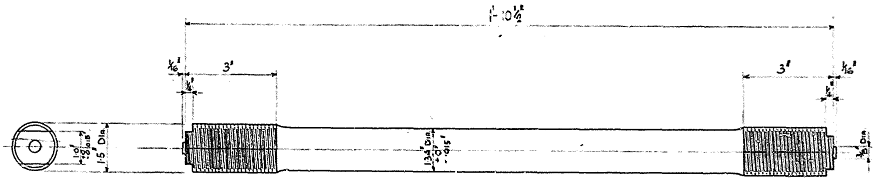


Fig 5.01: Original Bolt (from Drawing ACD2214 Rev. 3)

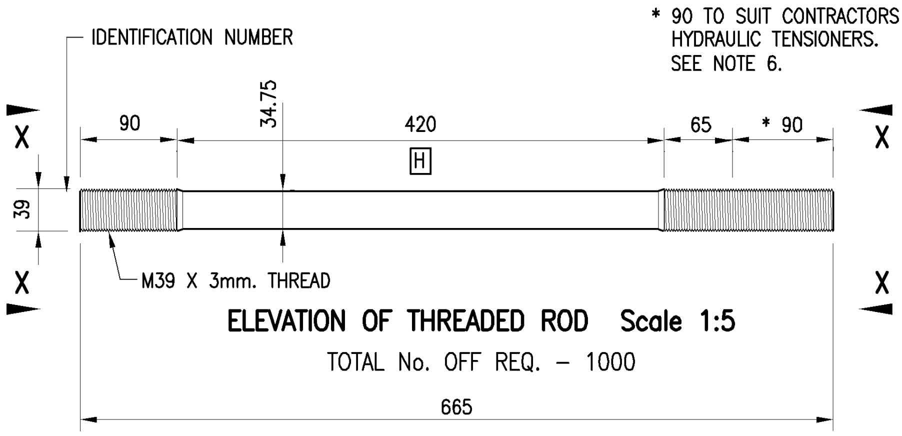


Fig 5.02: Replacement Bolt (from WAF Drawing 33111/AB/21)

The principal dimensions and cross sectional areas are given in Table 5.01. It can be seen that the change from imperial to metric threads has resulted in a 6.5% increase in thread tensile stress area and 4.2% increase in cross sectional area in the waisted shank. Therefore this should not have any detrimental effect.

BOLTS	Diameter	Pitch	Thread tensile stress area	Waisted shank diameter	Waisted shank area
Original Forth	1½", 38.1mm	BSF 8tpi, 3.175mm	965mm^2	1.34", 34.04mm	910mm^2
Replacement Forth	39mm	Fine, 3mm	1028mm^2	34.75mm	948mm^2
Change			+6.5%	+2.1%	+4.2%

Table 5.01: Bolt dimensions and areas

5.1.2 Nuts

Drawings of the original and replacement nuts are shown in Figures 5.3 and 5.4.

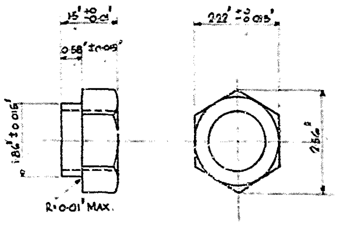


Fig 5.03: Original Nut (from ACD2214 Rev. 3)

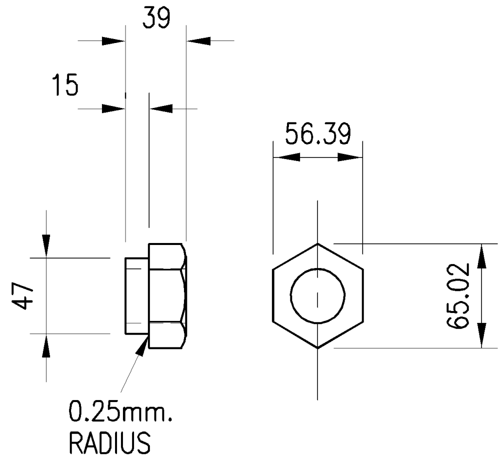


Fig 5.04: Replacement Nut (from WAF 33111/AB/21)

A comparison of the dimensions is presented in Tables 5.02 and 5.03. It would appear that the replacement nuts were closely based on the original nuts, with the dimensions simply being converted to metric. However, it can be noted that some of the dimensions have been rounded to the nearest whole number and that none of the tolerances have been carried across.

NUTS	Width across flats	Height of whole nut	Height of cylinder	Diameter of cylinder	Fillet Radius
Original Forth	56.39mm +0/-0.38mm	38.1mm +0/-0.25mm	14.73mm ±1.27mm	47.24mm ±0.38mm	0.254mm max
Replacement Forth	56.39mm No tolerance	39mm No tolerance	15mm No tolerance	47mm No tolerance	0.25mm

Table 5.02: Nut dimensions 1

NUTS	Cylinder stress area	Hexagon stress area
Original Forth	$673mm^2$	$1674mm^2$
Replacement Forth	$599mm^2$	$1618mm^2$
Change	-11.0%	-3.3%

Table 5.03: Nut dimensions 2

It was noted above that the change from 1.5 inch to M39 resulted in a slightly increased size of the bolt. However, in keeping the same size of the nut has had the consequence of reducing the cross sectional areas. In particular the cross sectional area of the cylindrical portion of the nut has reduced by 11%.

5.1.3 Washers

Drawings of the original and replacement washers are shown in Figures 5.05, 5.06 and 5.07.

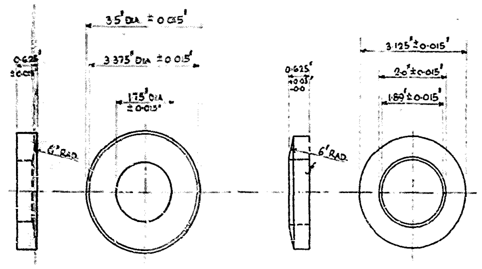


Fig 5.05: Original Washers (from ACD2214 Rev. 3)

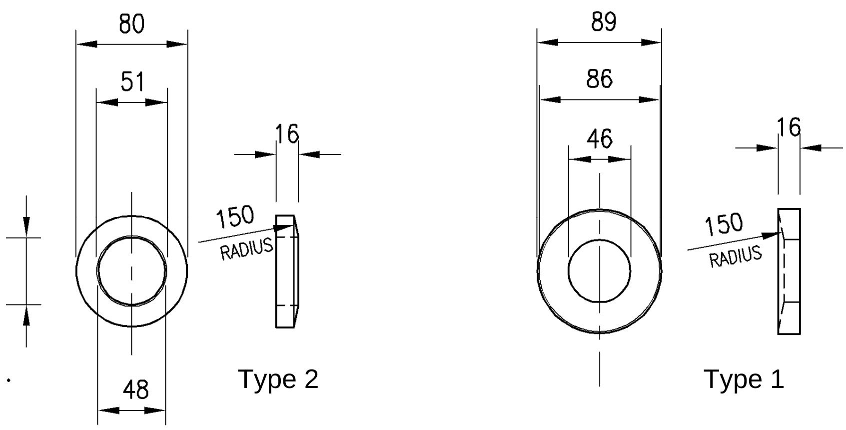


Fig 5.06: Replacement Washer – Dead End (from WAF 33111/AB/21)

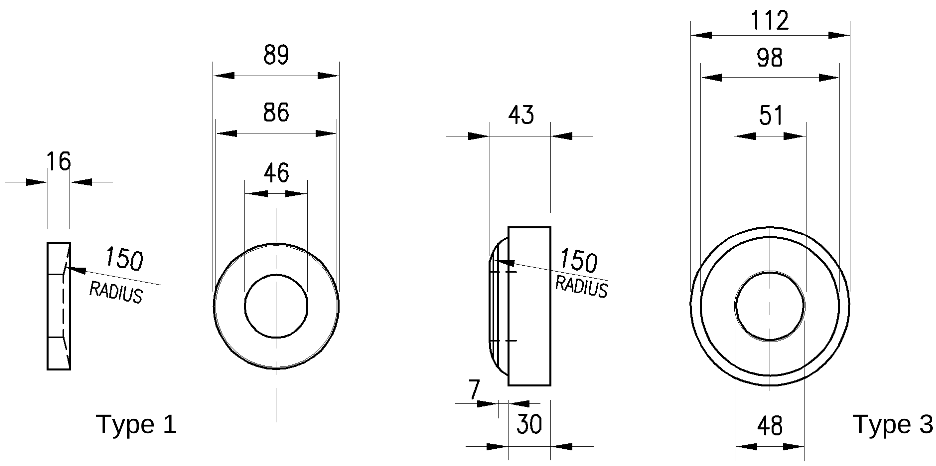


Fig 5.07: Replacement Washer – Live End (from WAF 33111/AB/21)

The dead end washers have similar dimensions to the original washers, whereas the live end washers have a greatly enhanced convex washer to accommodate the tensioning jack.

5.1.4 *Dimensional checks on removed bolts*

Various spot checks were made of the actual dimensions of the bolts, nuts and washers removed from the bridge. All dimensions were found to be close to the drawing values.

5.1.5 *Comparison of Nut Dimensions with Various Standards*

For comparison, the size of the original nuts has been compared with standards applicable at the time. These include BS 916:1953 (Black bolts, screws and nuts), BS 1083:1951 (Precision hexagon bolts, screws, nuts and plain washers) and BS 3139:1959 (High strength friction grip bolts). This is summarised in Table 5.04.

Standard	Size	Width across flats		Thickness	
		max	min	max	Min
BS 916	1.5" BSF	2.220", 56.39mm	2.175", 55.25mm	1.375", 34.93mm	1.315", 33.40mm
BS 1083	1.5" BSF	2.220", 56.39mm	2.200", 55.88mm	1.375", 34.93mm	1.355", 34.42mm
BS 3139	1.5" UNC	2.375", 60.33mm	2.330", 59.18mm	1.505", 38.23mm	1.433", 36.40mm
Forth original	1.5" BSF	2.220", 56.39mm	2.205", 56.01mm	1.500", 38.10mm	1.490", 37.85mm

Table 5.04: Comparison of nut dimensions with standards current at time of construction

It can be seen that the original Forth cable band bolt nuts have plan dimensions in line with black and precision bolts, but with an increased thickness of 0.125 inches, making it the same as a friction grip nut. The increase in thickness of 0.125 inches is the same as was used for a standard Roberts nut – see Section 4.

A similar comparison has been made using the replacement nuts and current standards. BS4190:2001 (ISO metric black hexagon bolts, screws and nuts) and BS3692 (ISO metric precision hexagon bolts, screws and nuts) are the metric equivalents of BS916 and BS1083. BS EN 14399-3:2005 (High-strength structural bolting assemblies for preloading – Part 3: System HR – Hexagon bolt and nut assemblies) is the latest standard covering high strength friction grip bolts. These are summarised in Table 5.05.

Standard	Size	Width across flats		Thickness	
		max	min	max	Min
BS 4190	M39x4	60.0mm	58.8mm	31.0mm	30.0mm
BS 3692	M39x4	60.0mm	59.26mm	31.0mm	30.38mm
EN 14399-3	M39x4*	65.0mm*	63.5mm*	33.5mm*	31.7mm*
Forth new	M39x3	56.39mm	56.39mm	39.0mm	39.0mm

* Size not covered by standard – extrapolated from other smaller sizes

Table 5.05: Comparison of nut dimensions with current standards

It would appear that by modern standards, the plan dimensions of the new Forth nuts are slightly smaller than black and precision nuts, and much smaller than HSFG nuts.

5.1.6 *Comparison of nut dimensions with other suspension bridges*

A comparison has also been made with similar style nuts used on cable band bolts in other suspension bridges. Some dimensional information is provided in Table 5.06

NUTS	Size	Width across flats	Height of whole nut	Height of cylinder	Diameter of cylinder	Fillet Radius
Forth original	1.5 inch	56.39mm	38.1mm	14.73mm	47.24mm	0.254mm max
Forth replacement	M39x3	56.39mm	39mm	15mm	47mm	0.25mm
Severn replacement	M36x3	56mm	40mm	17mm	45mm	0.2mm max
Humber	M36x3	65mm	48mm	18mm	53mm	0.3mm max
Bosporus 2	M36x3	65mm	48mm	18mm	53mm	3mm

Table 5.06: Comparison of nut dimensions with other suspension bridges

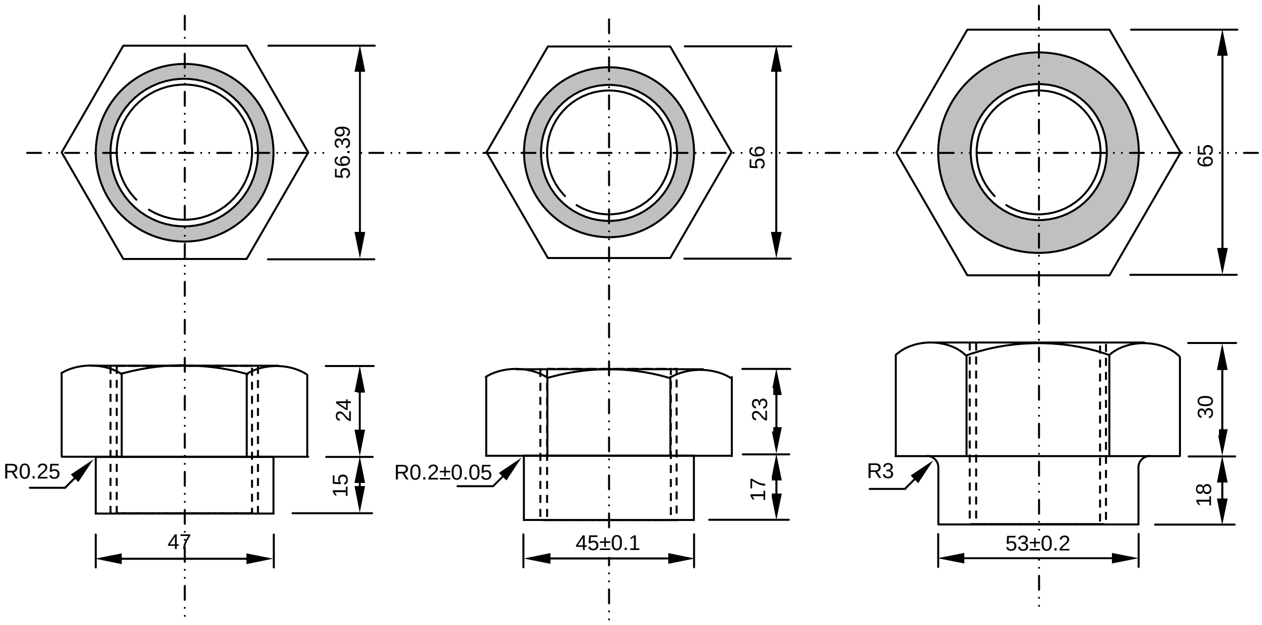


Fig 5.08: Comparison of nut sizes on various suspension bridges

It is interesting to note that replacement nuts for the Severn Bridge are broadly the same size as the replacement nuts on Forth, however, there is a difference in that the Severn nuts are for M36 bolts and the Forth nuts are for M39 bolts. The M36 bolts used at Severn were tensioned using a manual torque wrench to 68 tonnes therefore the stress in the nut is approximately 15% lower. The nuts for Bosporus 2 are very much larger in comparison with the others, and are believed to have been based on Humber, although the root radius has been significantly increased to 3mm.

5.2 Steel Material

5.2.1 Original Bolt Specification

The specification for the original material was as follows:

- Bolt – En24V to BS 970
- Nuts – En16R to BS970
- Washers – En16R to BS970

Both these steels were termed "alloy steels", and En24 is a 1.5% nickel-chromium-molybdenum steel and En16 is a manganese-molybdenum steel. The final letter indicates the tempering condition – R has a 45/55 ton tensile strength and V a 65/75 ton tensile strength. The properties were specified as follows (BS 970: 1947):

Steel	UTS Tons/sq.in. (N/mm^2)	YS Tons/sq.in. (N/mm^2)	Elongation %	Izod Ft-lb (Joules)	Brinnell Hardness
En16R	45 min (695 min)	*34 min (525 min)*	22 min	40 min (54)	*201/255*
En24V	65 min (1005)	*52 min (800)*	16 min	35 min (47)	*293/341*

Note: the yield stress and Brinnell hardness quoted in italics were representative values and were not intended for acceptance

Table 5.07: Mechanical properties of original bolts

The specified chemical composition is as follows:

Steel	C	Si	Mn	Ni	Cr	Mo	S	P
En16R	0.25/0.40	0.10/0.35	1.30/1.80	-	-	0.20/0.35	0.05max	0.05max
En24V	0.35/0.45	0.10/0.35	0.45/0.70	1.30/1.80	0.90/1.40	0.20/0.35	0.05max	0.05max

Table 5.08: Chemical composition of original bolts

The following diagram has been copied from the Resident Engineer's report on the wrapping of the main cables, and has been included as it shows a load-extension diagram for the original cable band bolts. This diagram was derived from tests carried out at the Royal College of Science and Technology in Glasgow in 1962. Unfortunately there is no record of the strain at failure.

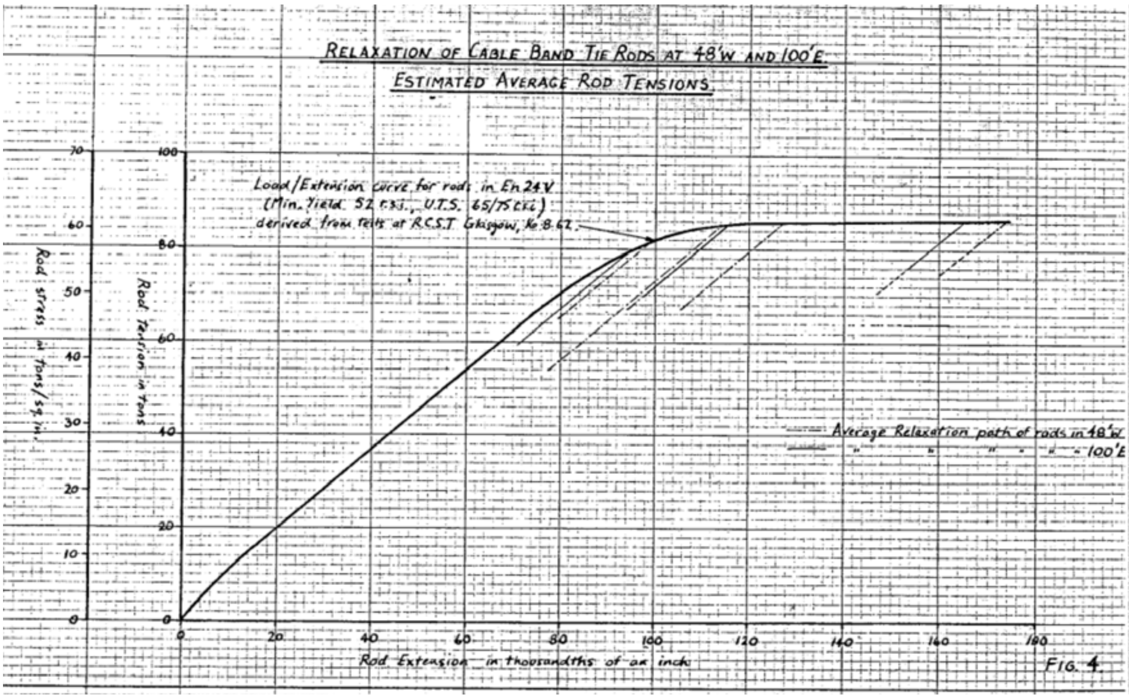


Fig 5.09: Load-extension relationship of original bolts

5.2.2 *Replacement Bolt Specification*

The specification for the replacement material was as follows (copy in Appendix B):

- Bolt – 826M40X to BS 970
- Nuts – 826M40W to BS970
- Washers – 826M40W to BS970

826M40 is also an alloy steel, and is equivalent to En26, a 2.5% nickel-chromium-molybdenum (high carbon) steel. The properties are specified in BS970: Part 3: 1991.

Steel	UTS N/mm^2	YS N/mm^2	Elongation A on GL $5.65\sqrt{S_0}$ %	Izod Joules	Brinnell
826M40X	1150 to 1300	1020 min	10 min	34 min	341 to 401
826M40W	1075 to 1225	940 min	11 min	40 min	311 to 375

Table 5.09: Mechanical properties of replacement bolts

The reason for the change in material specification is not known, however, it is possible that it was desired that the new bolts would be tensioned within the elastic region, rather than utilising the plastic region. Reference to Figure 5.09 above shows that a steel with a higher yield stress would be required to keep within the elastic zone at a bolt tension of 80 tonnes. The use of 826M40 instead of 817M40 (En24) is a logical step and is the same material used for the replacement Severn Bridge bolts. It should be noted that with each steel and temper there is an upper limiting thickness, as shown in Table 5.10.

Steel	Condition	Size mm (diameter, across flats or thickness)
817M40 (En24)	V W X	>13 ≤63 >6 ≤29 >6 ≤29
826M40 (En26)	V W X	>63 ≤150 >29 ≤150 >29 ≤150

Table 5.10: Limiting thicknesses

For the sizes required for the cable band bolts it can be seen that 817M40 is not available in conditions W or X, which presumably led to the choice of 826M40.

The specified chemical composition is as follows:

Steel	C	Si	Mn	Ni	Cr	Mo	S	P
826M40X	0.36/0.44	0.10/0.40	0.45/0.70	2.30/2.80	0.50/0.80	0.45/0.65	0.035max	0.040max
826M40W	0.36/0.44	0.10/0.40	0.45/0.70	2.30/2.80	0.50/0.80	0.45/0.65	0.035max	0.040max

Table 5.11: Chemical composition of replacement bolts

5.2.3 *Replacement Bolt Quality Assurance Records*

The quality assurance records for the bolt, nut and washer manufacture have been reviewed. All of the bolts, nuts and washers types 1 and 2 (small concave and convex) came from the same cast (B4013R), with the remaining washers type 3 (large convex) from another cast (B4012). Examination of cast B4013R shows that the chemical composition was within Specification and was generally similar to the results obtained by ESRT. Mechanical tests were carried out by British Steel on test pieces specially heat treated to simulate the treatment to be given to the production batch, and these also showed all the material to be within the Specification. Following heat treatment of material to be used in the production further mechanical tests were carried out and these are summarised below.

BOLTS 41 dia bar	Yield stress	Tensile strength	Elongation %	Reduction of Area %	Hardness HB	Toughness Izod
Spec	1020	1150-1300	>10		341-401	25
Test	1170	1240	13.4	55.9	363	37, 39, 38
NUTS 70 dia bar	Yield stress	Tensile strength	Elongation %	Reduction of Area %	Hardness HB	Toughness Izod
Spec	940	1075-1225	>11		311-375	27
Test	1008	1113	15.0	60.5	331	62, 62, 60
WASHERS #1 93 d bar	Yield stress	Tensile strength	Elongation %	Reduction of Area %	Hardness HB	Toughness Izod
Spec	940	1075-1225	>11		311-375	30
Test	1060	1140	12.5	57.4	341	51, 53, 50
WASHERS #2 83 d bar	Yield stress	Tensile strength	Elongation %	Reduction of Area %	Hardness HB	Toughness Izod
Spec	940	1075-1225	>11		311-375	30
Test	1090	1189	15.0	56.0	352	46, 46, 46
WASHERS #3 135 d bar	Yield stress	Tensile strength	Elongation %	Reduction of Area %	Hardness HB	Toughness Izod
Spec	940	1075-1225	>11		311-375	30
Test	1002	1174	14	49.0	341	46, 46, 46

Table 5.11: Mechanical properties of replacement bolts

Cast	C	Si	Mn	Ni	Cr	Mo	S	P
B4013R	0.41	0.24	0.58	2.38	0.65	0.55	0.032	0.011
B4012	0.395	0.23	0.69	2.51	0.65	0.54	0.030	0.007

Table 5.12: Chemical composition of replacement bolts

All the material was in accordance with the specification.

Spot checks of the cadmium plating process showed records of the careful heating process to minimise hydrogen embrittlement and plating thicknesses within specification. The plating thicknesses appeared to be measured as averaged over an area.

Prior to the main production run, 10 complete nut, bolt and washer assemblies were tensile tested, initially up to yield, and then to failure. All 10 bolts failed within the portion of waisted shank, as expected. The failure loads varied from 1009kN to 1182kN, equivalent to stresses of 1064 to 1247N/mm^2 on the shank area. Unfortunately, there is no record of the elongation. Proof load tests were also carried out on 5 nuts, with a load of 1100kN being applied for 15 seconds, after which it was found that all nuts still rotated freely.

The load-extension graphs from a typical tensile test are shown below.

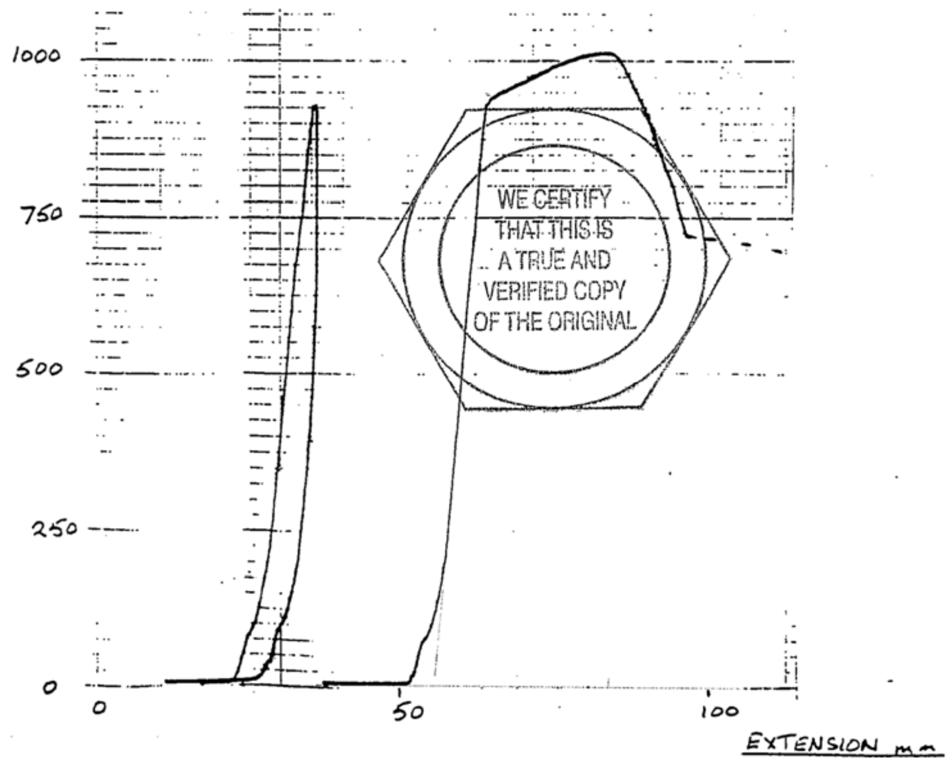


Fig 5.10: Load-extension curve for test 98HC357C (autographic recording)

In Figure 5.10 the peak on the left shows the loading and unloading during the first test up to yield point, and the peak on the right shows the test to failure. The extension along the x axis is believed to be the machine extension, and not just the bolt extension. A table of force and extension data was provided and this has been plotted to determine Young's Modulus.

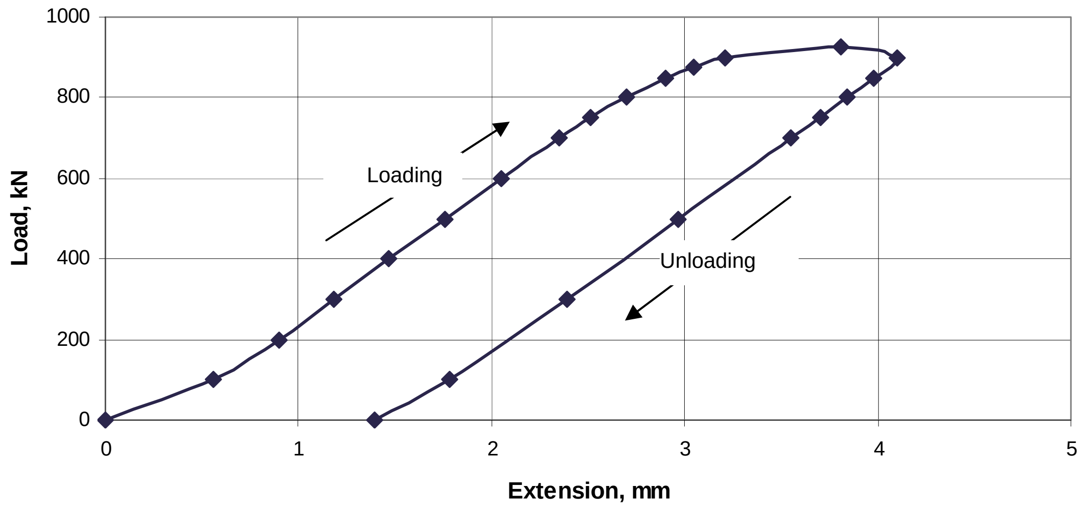


Fig 5.11: Load-extension curve for test 98HC357C (plotted from data)

Young's modulus has been calculated using best-fit curves from the ten tensile tests using both loading and unloading data. Careful allowance was made for the presence of the washers and likely effective position of load transfer between bolt and nuts. The histogram distribution below in Figure 5.12 appears realistic, with a centre of between 205 and 210 kN/mm^2.

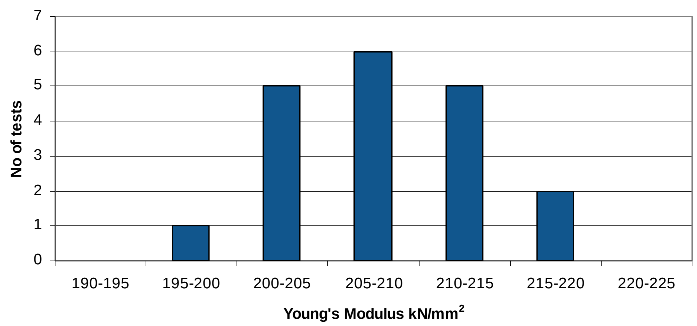


Fig 5.12: Distribution of Young's Modulus from pre-production tests

5.2.4 *Ductility*

Ductility is a key attribute of steel and is a measure of the strain that can be endured beyond yield prior to fracture. It is an important aspect of the design of the nut and bolt assembly.

Measurement of elongation is carried in accordance with standard test procedures and must be regarded as indicative of the behaviour of the steel.

Normal structural steels will have elongations after fracture of at least 20%, however, this tends to reduce as the tensile strength increases.

To illustrate the effect on ductility of increasing strength, some data on wrought steels has been taken from BS971:1950, Commentary on British Standard Wrought Steels, En Series. In addition to the specification values from BS 970:1947 (as would have been applicable for the original bolts), there is some data from many tests carried out on steel samples. One point to note is that the standard test carried out at that time used a test piece with a gauge length equal to $4\sqrt{A_0}$, whereas the current standards use a gauge length equal to $5.65\sqrt{S_0}$, A_0 and S_0 being the original cross sectional areas. This produces a different result, i.e. the elongations from the two editions of BS 970 are not directly comparable.

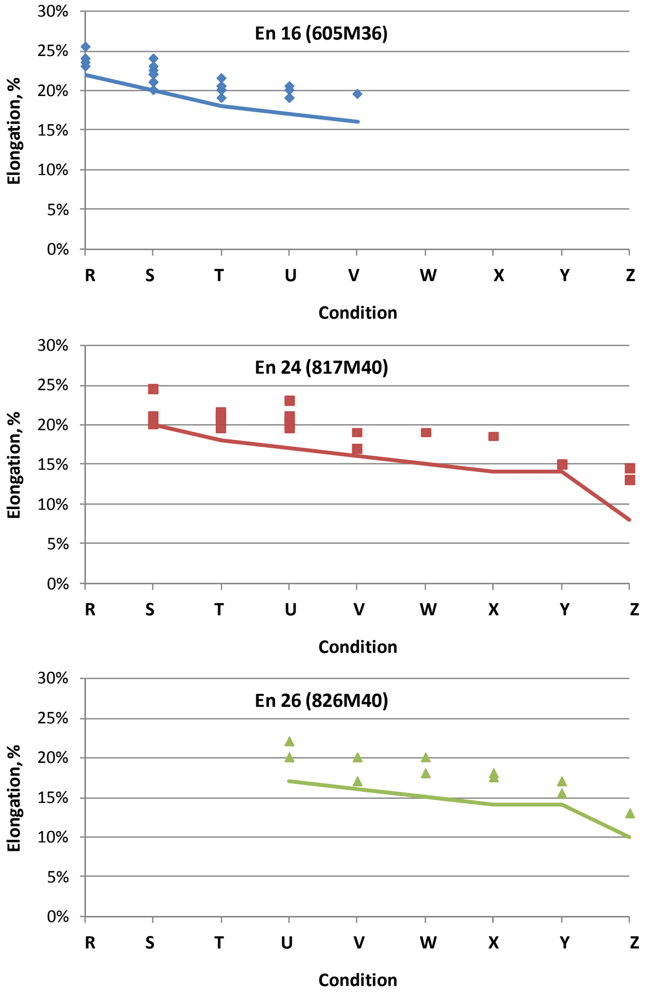


Fig 5.13: Elongations of steel samples, from BS 971:1950

In Figure 5.13, the individual points represent the test data, and the solid lines are the minimum specified elongations. The minimum specified values are identical for all steels, with the exception of Condition Z.

The steel for the original nuts (En 16R) had a minimum specified elongation of 22%, but results up to 25% have been typically recorded. The steel for the replacement nuts (En 26W) had a minimum specified elongation of 15%, with test results of up to 20%.

Figure 5.14 below compares the minimum specified elongations in the 1947 and 1991 editions of BS 970. As discussed above, the difference relates to a change in the standard test piece. Also plotted is the elongation recorded in the mill certificate of 15% (well above minimum specification of 11%), and also the elongations from the mini tensile samples cut from the first failed nut (54NW – 9.9%) and companion un-failed nut (10.5%). Note that these are much less than the mill certificate and appear to be below specification, however, the small size of the sample may be a contributory factor.

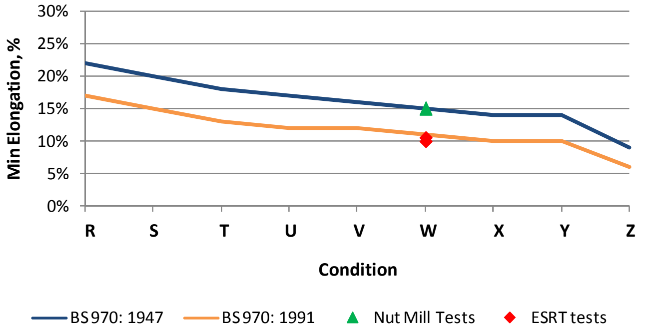


Fig 5.14: Comparison of Specified Minimum Elongations

5.2.5 *Toughness*

The toughness of the steel has been measured using the Izod impact test. This is broadly similar to the Charpy V-notch impact test, but the notched sample is held as a cantilever rather than as a beam. The value of energy absorbed is a measure of the toughness, but it cannot be used as a design value. The 1947 and 1991 versions of BS 970 essentially have the same specified Izod figures, apart from rounding associated from converting from ft-lb to Joules.

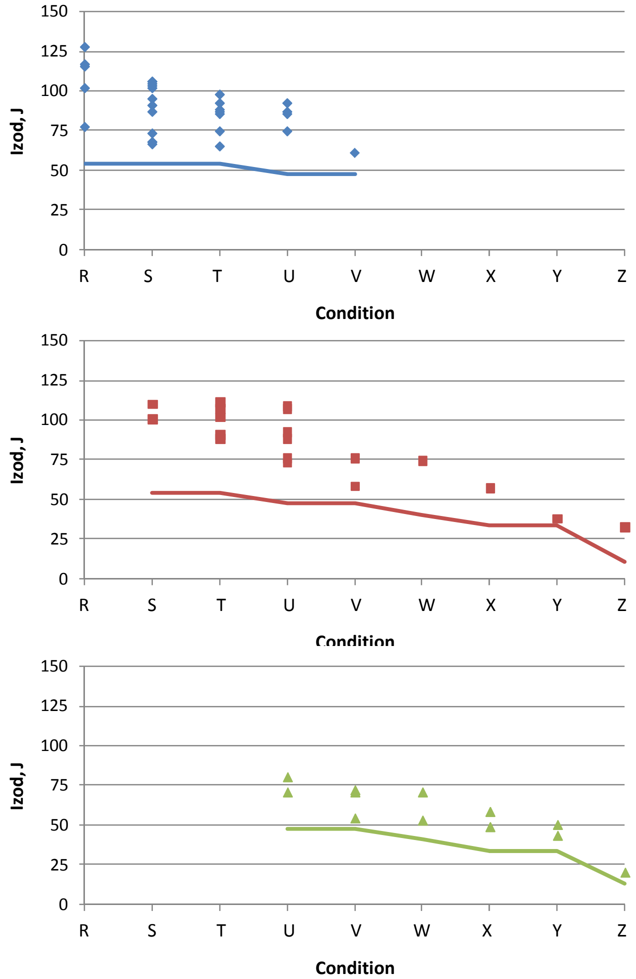


Fig 5.15: Izod values of steel samples, from BS 971:1950

Figure 5.15 is of a similar construction to Figure 5.13 and uses test data taken from BS 971: 1950.

The steel for the original nuts (En 16R) has a minimum Izod value of 54J, but results up to 125J have been typically recorded. The steel for the replacement nuts (En 26W) has a minimum specified Izod value of 40J, with test results of up to 70J.

Figure 5.16 below plots the combined specified minimum Izod value with the points from the mill tests. No tests were carried out by ESRT. It can be seen that the recorded impact energies were all above the required minimum.

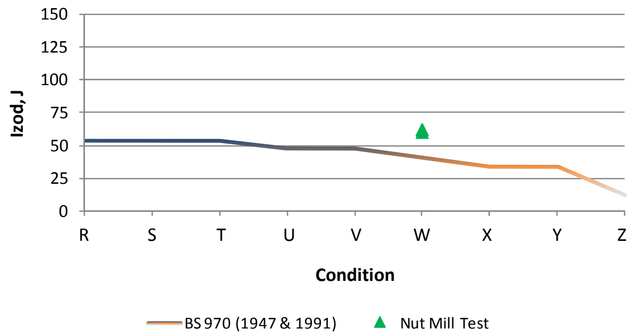


Fig 5.16: Izod Values – Replacement Nut Mill Tests and Specification

5.3 Method of Tensioning

5.3.1 Original Bolts

The original bolts were tensioned using a torque multiplying head and a ratchet lever arm. The applied torques were estimated by getting a man of known weight to support himself at various distances along the lever arm when it was horizontal. The applied torque was between 1500 and 2500 ft-lb (2035 and 3400 Nm). It was found that the majority of the nuts could be turned at the lower end of this torque range.

The ICE Proceedings state that these bolts were tensioned to 65 tons, however, in the Resident Engineer's Office Interim Report on Erection of Steelwork, the tension is clearly stated as being 80 tons. The tensioning procedure is described in the RE's Report on Wrapping which states "The Specification required retightening of all tie-rods when the estimated tension fell below 90% of the required 65 tons at the completion of the cable wrapping, and finally by a half turn rotation of one nut when all the dead load was on the bridge". An earlier report explained that the rods were initially tightened up to yield (approx 80 tons tension) and were then retightened more frequently than the specification requirement in an effort to accelerate the slow compaction of the cables and so reduce the amount of relaxation which would take place after final retightening.". The RE's Report gives much information on bolt relaxation as bridge construction continued and includes this diagram indicating the frequency of retightening experienced.

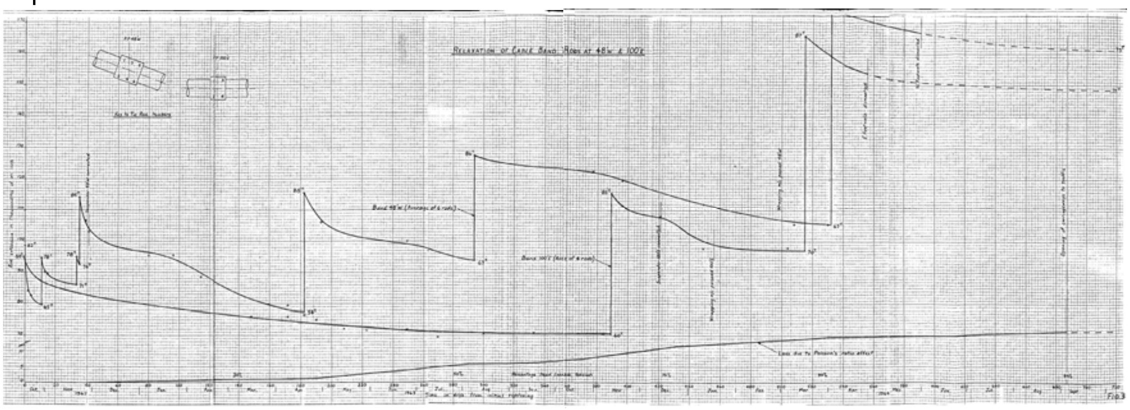


Fig 5.17: Typical bolt relaxation during construction

The relaxation was thought to arise from reduction in cable diameter as from Poisson's effect as cable tension increased, slow compaction of the cable, increments in suspender load and cable wrapping.

It should be noted that the tension of 80 tons brings the bolt up to yield and the further half turn ensures that the bolt is fully taken into the plastic region. This philosophy was subsequently adopted in all later Freeman Fox designed suspension bridges. One consequence of this is that if there is any misalignment, the elastic moments that arise from this will disappear as the stress is redistributed.

5.3.2 Replacement Bolts

The Specification for the replacement bolts requires a final load in each bolt to be 910kN (+2.5%, -0%). However, this appears to have changed by the time of carrying out the work on site with the Monberg and Thorsen (M&T) method statement giving a final load of 812kN. This is compatible with the load of 80 tons in the original bolts, prior to their final half turn.

A copy of Monberg and Thorsen Work Instruction 1.722 detailing the procedure for installing and tightening the replacement bolts was obtained from FETA's archives (copy in Appendix C). It is summarised as follows.

- All old bolts were de-tensioned by one half turn.
- A pair of old bolts (comprising one in upper row and corresponding one in the lower row) were fully de-tensioned and removed.

- A pair of new bolts were inserted and tensioned together to approx 200kN, as measured by pressure gauge at 300 bar.
- Remaining pairs of bolts were de-tensioned and removed, new pairs of bolts inserted and tensioned to approx 200kN.
- Bolt tensioners installed on all bolts and simultaneously tensioned to a gauge reading of 1150 bar, equivalent to 812kN.
- Elongation measured using Hydratight bolt scanner, and E value calculated.
- All nuts uniformly tightened by hand and jack pressure released.
- Elongation is re-measured using bolt scanner and force calculated using calculated E value.
- If the calculated force in any bolt is less than 750kN, then the Engineer will confirm whether to raise the pressure on all bolts to a suitable level (max 1200 bar, 850kN) and procedure repeated.

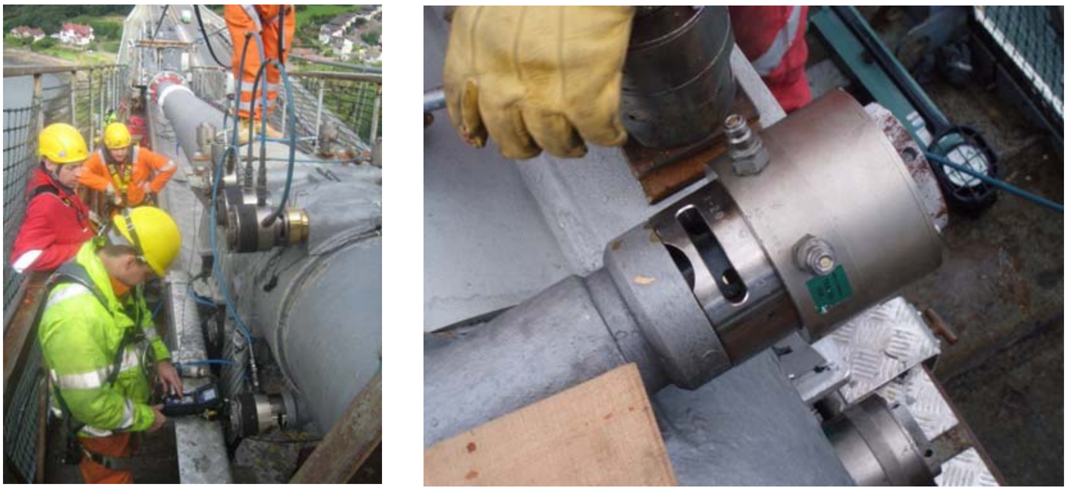


Fig 5.18: Hydraulic tensioning equipment as used to replace failed nuts

On the face of it, the above procedure appears reasonable. However, on closer examination it appears that the incorrect bolt length may have been used. Whilst the bolt scan measures the entire length of the bolt, not all of the length is being stressed. Figure 5.19 illustrates the assembled bolt. The nominal width of the cable band is 451mm, over which the spherical washer sets are placed, and the nuts partially fit within these. We understand the designer has defined the effective length of the bolt to be 549mm. In a calculation of the bolt extension due allowance must be made for part of the length being the waisted shank and the remainder comprising the slightly larger diameter threaded portion. This has been done by taking proportions of 420/549 and 129/549 respectively.

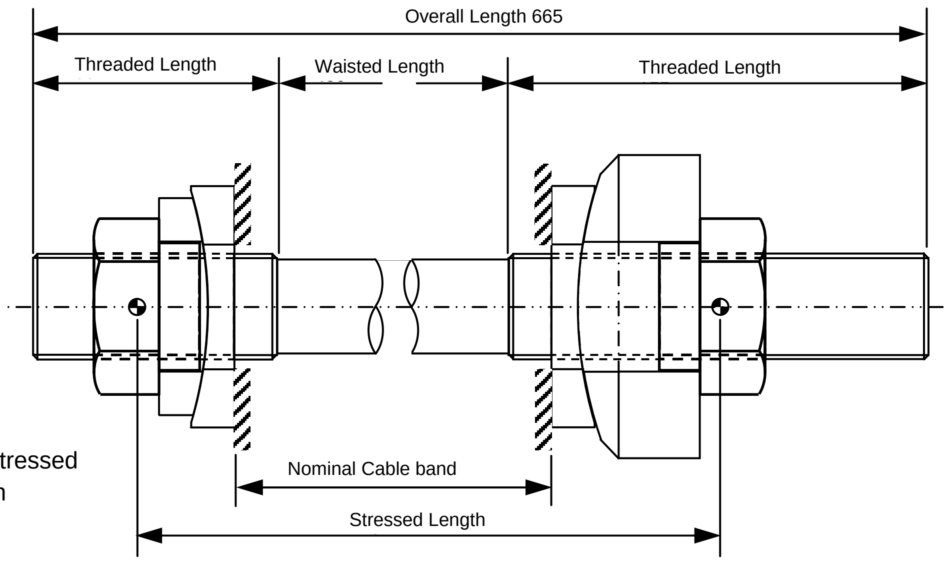


Fig 5.19: Bolt stressed length

However, during the tensioning procedure the extension is first measured whilst the tension is still being held by the jack, and there will be a longer length of bolt being stretched at that time. This is shown in Figure 5.20.

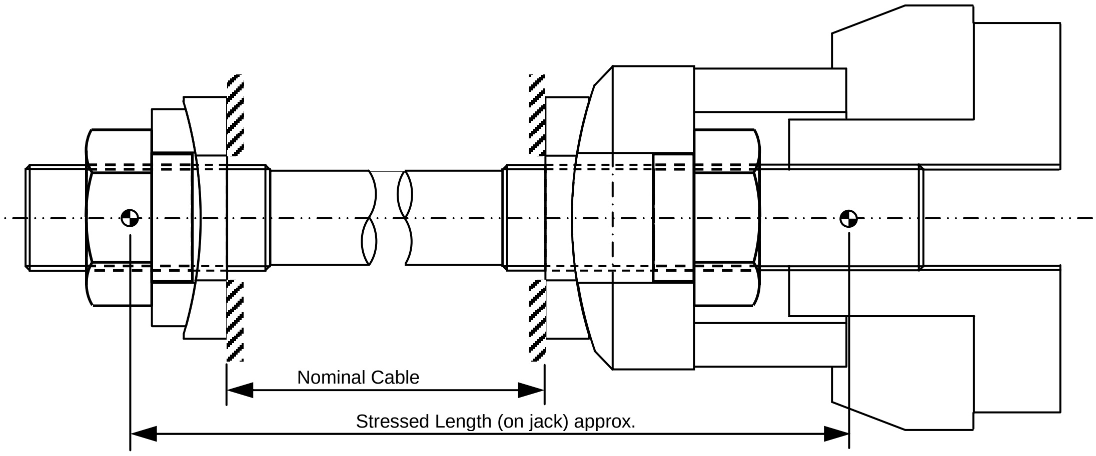


Fig 5.20: Bolt stressed length under jack

When calculating Young's modulus if the smaller 'nut to nut' (incorrect) length of 549mm was used instead of the actual tensioned 'nut to jack' length of about 600mm, then the calculated modulus would be smaller than the true value.

The use of hydraulic tensioning equipment instead of a manual torque wrench could be a contributory factor in the nut failures. A torque wrench will input load into the bolt and nut relatively slowly (and will also introduce some torsion into the system via thread and washer face friction), whereas a hydraulic tensioner will apply load much more quickly. It is also possible for load to be cycled as attempts are made to obtain the correct tensions.

The presence of the jacking stool and sleeve to run the nut down totally obscure the fit of the nut on the washer, and thus it will not be possible to check if the nut is sitting squarely on the washer.

5.4 Analysis of Bolt Tensioning Results

5.4.1 Installation Programme

An analysis of all bolt tensioning records has been undertaken. Initially a check was undertaken of the bolt replacement programme to establish potential reasons for failure. For example, if the failed nuts had all been tensioned very early in the contract.

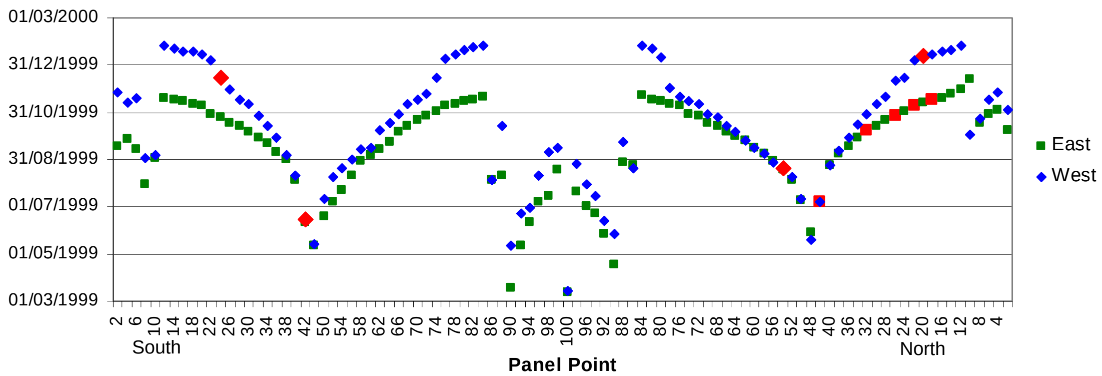


Fig 5.21: Bolt tensioning programme

Figure 5.21 shows that two bolts were installed quite early on (42SW and 42NW), however, the remainder were installed during the main production part of the contract. It can be seen that all the bolts were installed from the mobile gantries as they progressed down from the tower tops. Hence there does not appear to be anything of relevance from the installation programme.

5.4.2 *Analysis of Tensioning Records*

The records indicate a very large variation in the measured value of Young's modulus. Table 5.13 summarises the Young's Modulus, extension and force calculated from these for all installed bolts.

	Young's Modulus (kN/mm^2)	Final Extension (mm)	Calculated Force (kN)
Average	187	2.38	782
Minimum	150	2.01	697
Maximum	217	3.11	860

Table 5.13: Summary of bolt tensioning

Frequency distribution curves have been produced for Young's modulus, final extension and calculated force (Figures 5.22 to 5.24).

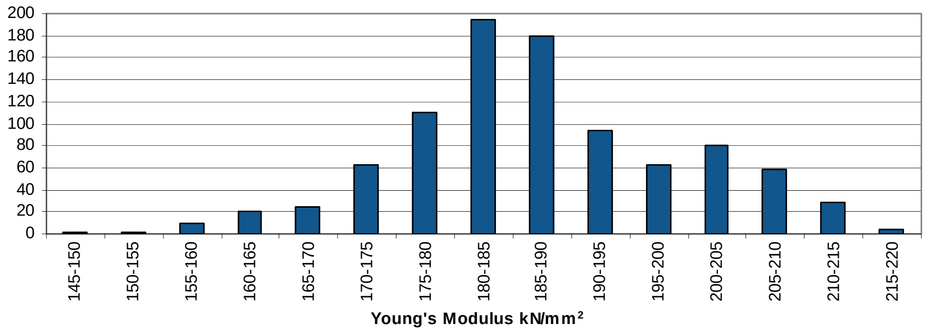


Fig 5.22: Distribution of Young's Modulus

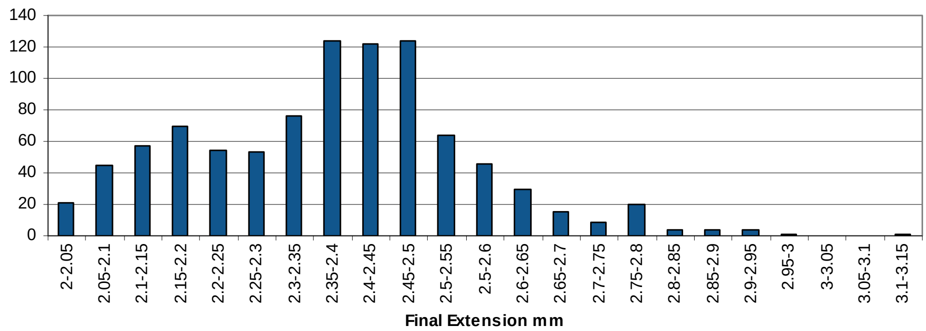


Fig 5.23: Distribution of Final Extension

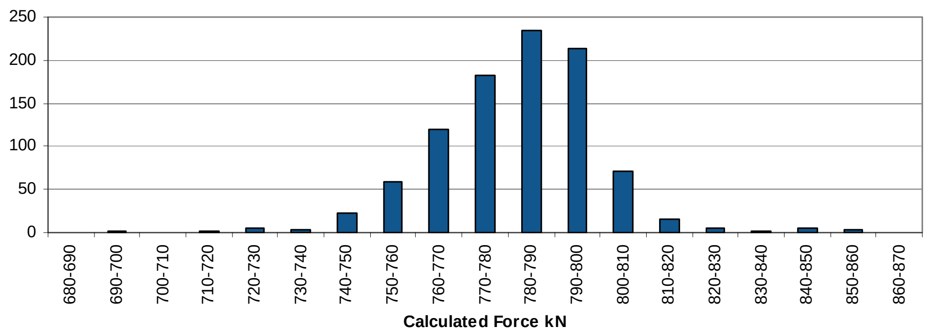


Fig 5.24: Distribution of Calculated Load

The range of Young's Modulus from 150 to 217 kN/mm^2 in Figure 5.22 is very much wider than would be expected. Comparison with Figure 5.12 for the pre-production tests suggests that the values determined during the tensioning are unrealistic. All material for the rods came from the same steel cast again suggesting there should not be any variation from the E values of 200 to 210 kN/mm^2 stated in BS 970.

A more reliable indication of the bolt load is to accurately measure the extension, but it can be seen from Figure 5.23 that there is a wide spread of extensions, from 2.01 to 3.11mm. The bolt extensions were measured using a proprietary ultrasonic scanner (Bolt scan). This is an electronic device or “black box” method of measurement as opposed to a more conventional physical measurement using a micrometer. The replacement bolts do not have a nipple or recess to allow the use of a micrometer, and it is not clear whether the end faces were machined square to the bolt axis.

The outcome of using the wide range of Young’s Modulus with the wide range of measured extensions is given in Figure 5.24 as the calculated bolt loads. This has a fairly narrow bandwidth, and apart from a couple of low outlying results, this would appear to present an ideal answer.

The initial bolt loads have been assessed using the more conventional approach of constructing an average load-extension diagram using the pre-production test results. This is shown in Figure 5.25, onto which the range of measured extensions has been added and the consequential range of calculated initial loads.

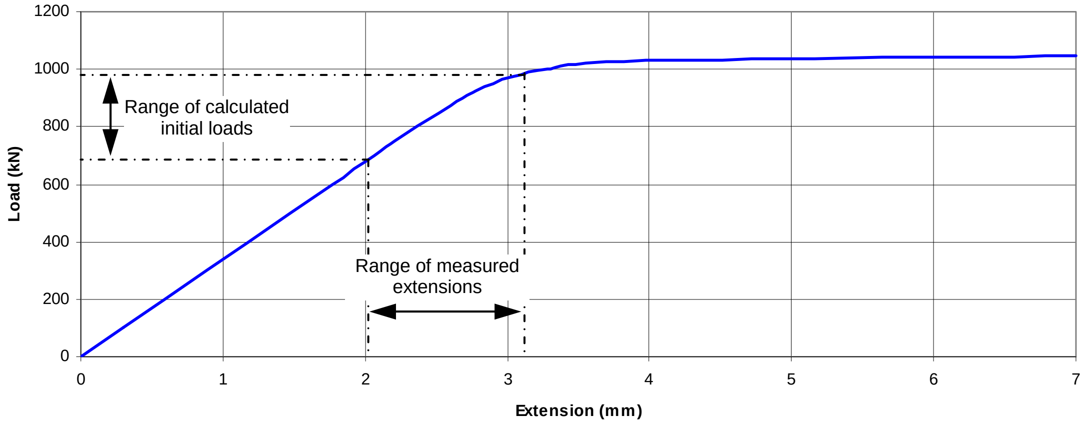


Fig 5.25: Estimated average load-extension relationship for replacement bolts

This diagram appears to confirm the designer’s intention of stressing within the elastic range of the bolts.

The distribution of calculated loads changes to the following.

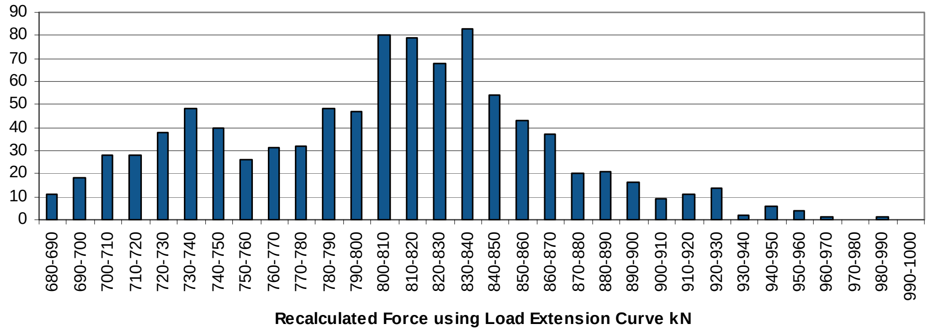


Fig 5.26: Distribution of Recalculated Initial Loads

Using this method produces a slightly higher average (805kN), but a much larger range (681 minimum to 981kN maximum).

As a check of the load extension curve developed from the pre-production test results, a comparison has been made with the load extension curve used for tightening the original bolts. As can be seen in Figure 5.27 there is great similarity between the two curves. The difference in slopes of the curves within the elastic region is due to slightly different cross sectional areas, and the height is of course related to the different tensile strengths.

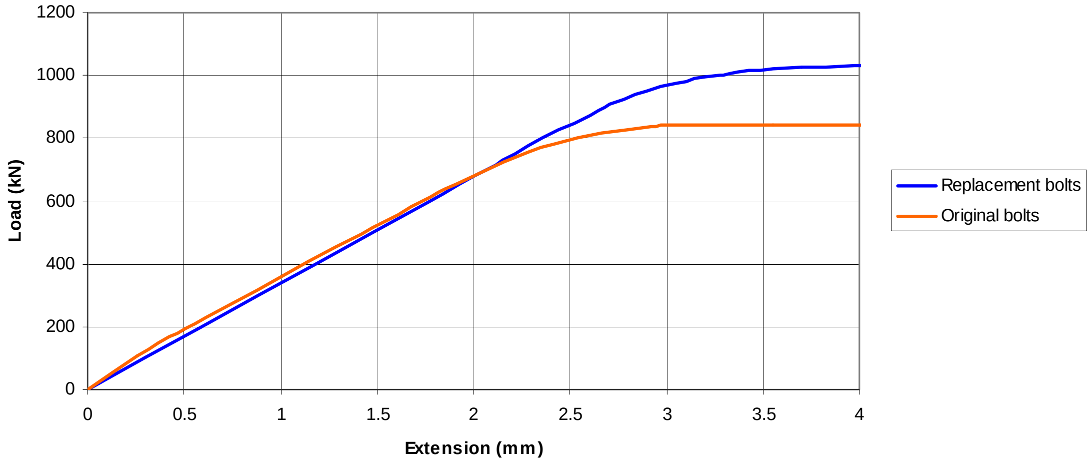


Fig 5.27: Comparison of Load-Extension curves for original and replacement bolts

5.4.3 *Check of Tensioning Records for Bolts with Broken Nuts*

A check has been made of the tensioning records of the bolts with broken nuts to establish if there are any pertinent differences that may have contributed to the failure of the nuts.

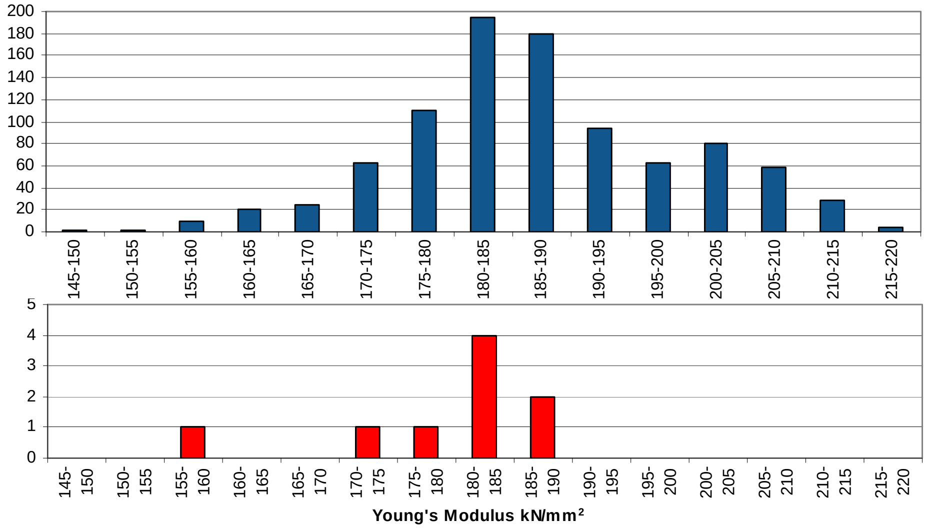


Fig 5.28: Distribution of Young's Modulus from all bolts and those with failed nuts

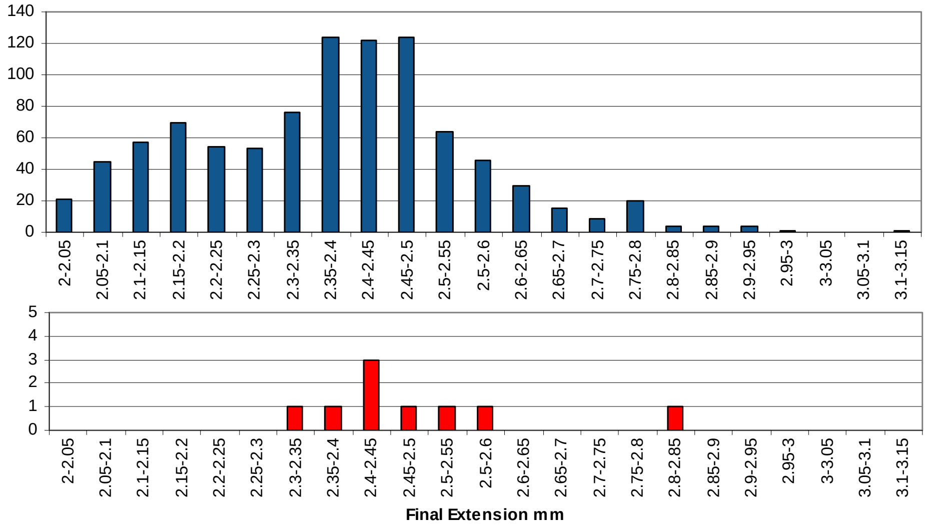


Fig 5.29: Distribution of Final Extensions from all bolts and those with failed nuts

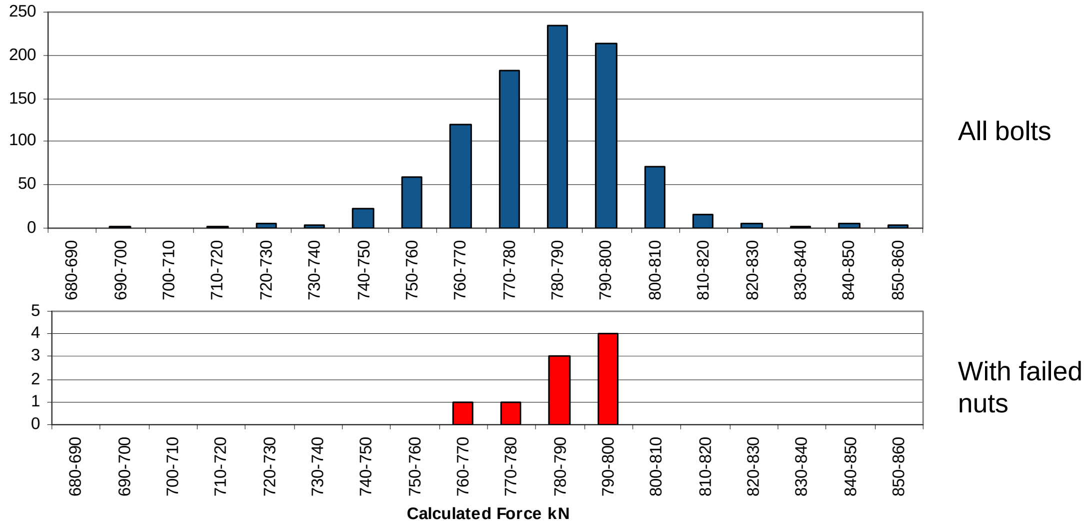


Fig 5.30: Distribution of Calculated Forces from all bolts and those with failed nuts

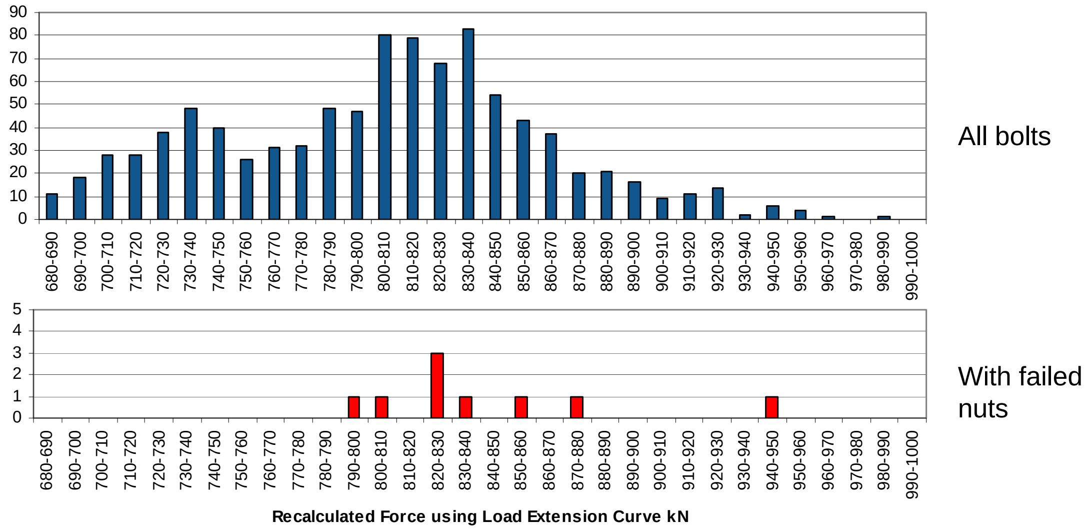


Fig 5.31: Distribution of Recalculated Forces using Load Extension Curve, from all bolts and those with failed nuts

5.5 Protective Treatment System

The specification for the replacement nuts, bolts and washers calls for cadmium plating with a minimum thickness of 25 microns.

Cadmium plating was a common surface treatment for nuts and bolts in the 1960s and was the usual coating for Roberts Bolts. It provides good protection to the underlying steel and does not tend to gall in the threads on tightening. However, there were a number of instances of Roberts Bolts failing in service as a result of hydrogen embrittlement, believed to arise from incorrect heat treatment following the plating process. The author has experience of such failures, which were believed to have occurred within six months of installation and stressing, and the bolts failed across the shank and not in the nuts.

The original cable band bolts on Forth were also cadmium plated, although the thickness is not known. Drawings of the cable band bolts used on Humber Bridge have been reviewed and indicate a cadmium thickness of 5 microns, which is likely to have been the thickness used on the original cable band bolts and Roberts Bolts in general.

The specification for the new bolts provides for proper heat treatment following the plating process, and there is evidence in the quality documentation supplied with the bolts that this was correctly carried out. This is further confirmed by ESRT's testing, which states that there was no evidence of hydrogen embrittlement in the fractures. Therefore we can conclude that hydrogen embrittlement arising from the cadmium plating is unlikely to be a contributing factor.

One point worth noting is that the full 25 micron thickness was required on the threads of the nuts and bolts, and that the specified thread fit (medium 6H/6g) was to be achieved after application of the plating. Given that cadmium is much softer than steel it is likely that the nuts and bolts would have developed a somewhat looser fit. ESRT also noted that the coating thickness was good on flat areas, but thinner in detail areas such as threads and corners.

5.6 Stress Concentration at Re-entrant Corners

The design of the nut features a re-entrant corner at the shoulder. ESRT believe that this is the site of the initiating circumferential cracks that ultimately lead to failure. In Section 5.1 the radius was 0.01 inches (0.254mm) in the original bolts and 0.25mm in the replacement bolts. These are typical of bolts used on other bridges, with the exception of Bosporus 2, where this was increased to 3mm.

To assess the potential stress concentration in this area reference has been made to Roark & Young, *Formulas for Stress and Strain*. The nearest approximation is for a solid circular shaft with a square shoulder and fillet. Figure 5.32 plots the stress concentration factor relative to the area of the shouldered down part for dimensions appropriate to the replacement nuts. (A broadly similar diagram is given in BS 5400: Part 10 for a flat plate with shoulders.)

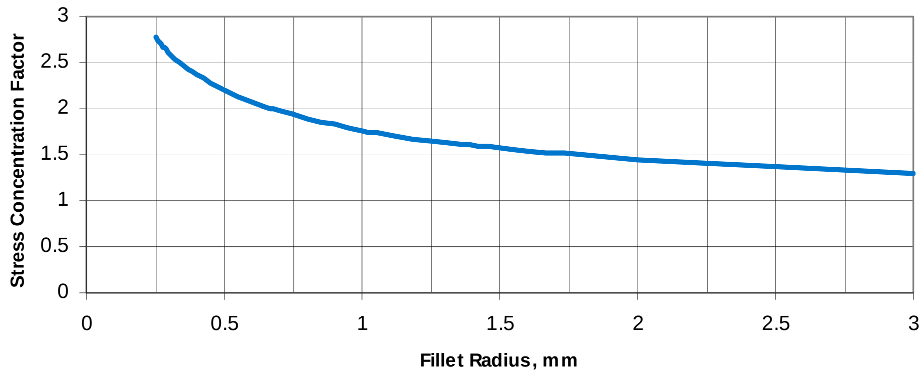


Fig 5.32: Calculated stress concentration factor at re-entrant corner (from Roark & Young)

The above figure suggests that a 0.25mm radius fillet could increase the axial stress locally by a factor of over 2.5 times. This is of course a simplistic analysis, but it does indicate how stresses that are normally within the elastic region could increase to beyond the tensile strength of the material. Some analysis has been carried out to establish stress levels within the nuts, and this is presented in the next section.

5.7 Analysis of Nut

It is recognised that the stress pattern within a nut will be of a very complex nature, and will be difficult to model with any accuracy. The interaction of the bolt and nut, and the transfer of load through the threads is particularly difficult with matters such as thread engagement and friction adding uncertainty.

Before reviewing results from any models, the principles of the structural action of normal and Roberts nuts will be presented.

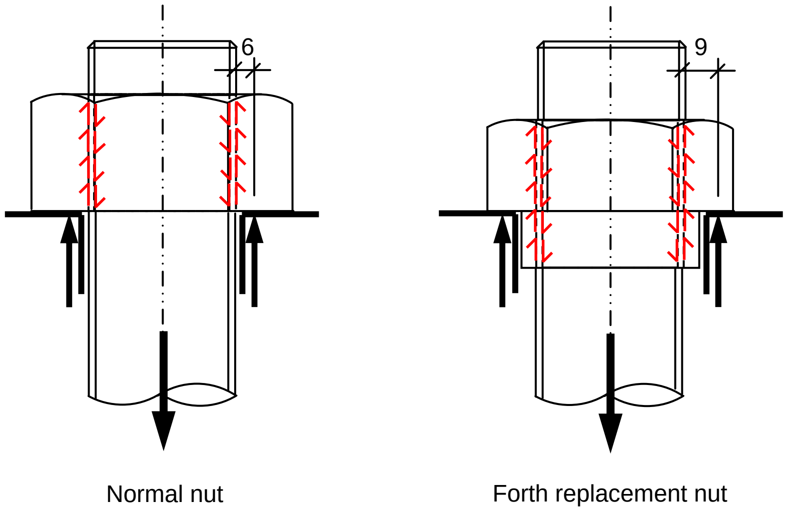


Fig 5.33: Force transfer in normal and Roberts nut

With a normal nut the axial tension in the bolt is transferred as a shearing action between threads into the nut. It can be seen in Figure 5.33 that there is a small eccentricity between the shearing action and the point of reaction at the base of the nut, which is estimated at about 6mm. This produces a moment in the nut wall, which is distributed over the full height of the nut (30mm).

In the replacement nut there is a similar load path, but it will be noted that the position of the reaction point on the shoulder of the nut is set further out, with an estimated eccentricity of about 9mm, i.e. 50% greater than a normal nut. Further the associated moment is resisted by the hexagonal part only, with a height of 24mm. Thus not only is the moment larger, but the section to resist it is smaller.

A series of 3D space frame models have been created to assess the stress conditions within the nuts. To assess their validity a check was made of the load distribution along the helix and compared with published data[1]. Figure 5.34 shows data calculated for a variety of load and support conditions – case D is appropriate.

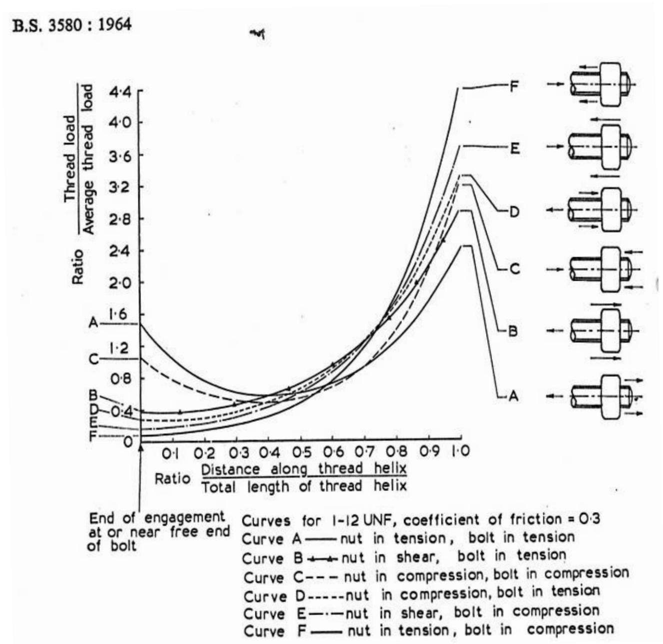


Fig 5.34: Theoretical load distribution along thread helix

[1] BS3580: 1964 Guide to design considerations on the strength of screw threads

A full normal style nut was modelled first to check if a similar distribution could be produced. The result is shown in Figure 5.35, and shows a reasonable comparison.

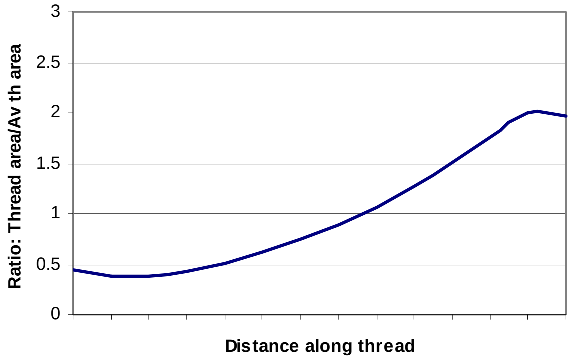


Fig 5.31: Calculated load distribution along thread helix for full normal nut

Substituting the Roberts nut produces a quite different result, as shown in Figure 5.35. The shouldered down section at the right hand side has produced a significant softening as might be expected, and overall the load distribution is virtually constant along the whole length of the nut.

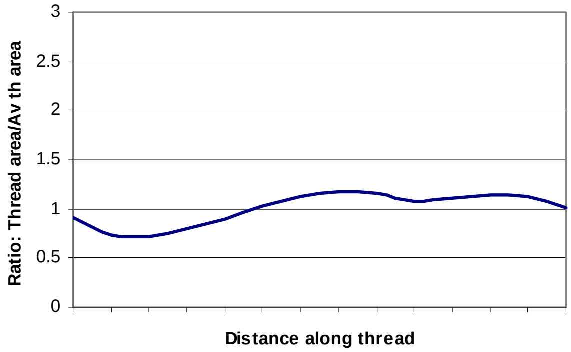


Fig 5.36: Calculated load distribution along thread helix for Roberts nut

The above two diagrams are based on the load being applied to the nut externally by the bolt, which is equivalent to either the situation at the dead end or if the bolt had been tightened using a spanner on the nut (but neglecting any torsion).

The hydraulic bolt tensioner will apply a load to the entire length of the bolt as it passes through the nut. Once at the correct load the nut is run down against the washer face, but it is not possible to tighten to any degree. It will attempt to engage threads along its length, but as the bolt is still in a stretched condition, the best engagement will take place in the threads adjacent to the washer. (To be completed….)

6 Other bolts potentially at risk

This study has also considered whether there might be other bolts and nuts subject to the problems covered in this report.

6.1 Hanger Holding Down Bolts

These bolts were replaced at the same time as the cable band bolts, as part of the hanger replacement contract.

Details of these bolts are given on WAF drawing 33111/AB/12 and the specification. Part of this drawing is reproduced below with the drawing of the original bolts.

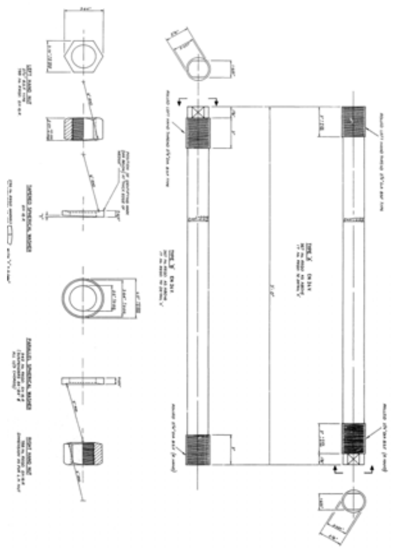


Fig 6.01: Original Hanger Holding Down Bolts

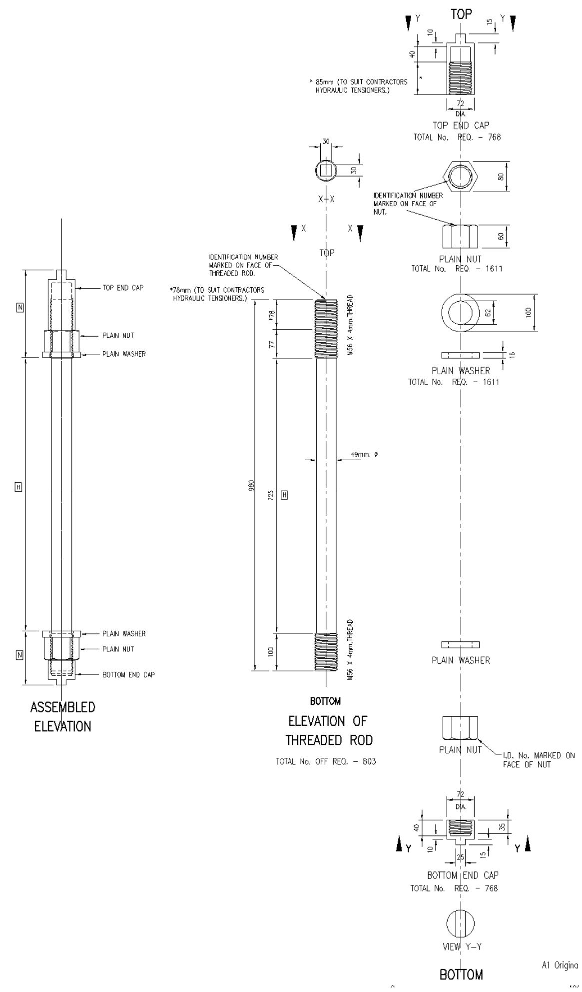


Fig 6.02: Replacement Hanger Holding Down Bolts

The original bolts were 2¼ inch BSF, turned down to 2.037 inch (51.74mm) between threaded ends, manufactured from En 24V steel. Curiously one end had a left hand thread and the other a right hand thread. This is believed to have been to suit the tensioning system, which tightened a pair of bolts together using a common hydraulic jack linked to two ring spanners, one on each nut. The nuts were of the standard pattern (i.e. not Roberts type) and were made from En 16R steel, 3.15 inch across flats and 2.25 inch high. One face was machined to a 6 inch radius to match a similar radius in the washer. The upper spherical washer was tapered to suit the horizontal plane of the hanger socket, with the bolt normal to the truss top chord. These were believed to be cadmium plated and tensioned to 90 tons.

The replacement bolts are M56x4, turned down to 49mm in the shank. They are thus slightly smaller than the originals (thread 56 c.f. 57.15mm, shank 49 c.f. 51.74mm). They are manufactured from 817M40V, directly equivalent to En 24V of the original. Both ends have normal right hand threads.

The replacement nuts are also standard pattern and are made of 605M36R, directly equivalent to En 16R of the originals. Their height is 60mm (c.f. 57.15mm) and width across flats of 80mm (c.f. 80.01mm). Given the slightly smaller thread diameter, the replacement nuts are dimensionally slightly larger than the originals.

The dimensions of the original nuts are consistent with the then standards (BS 916: 1953 – Black bolts, screws and nuts), with a width across flats of 3.15 inches, but the height was increased from 1.875 to 2.25 inches. Current standards give a width across flats of 85mm and a height of 45mm for a M56 nut. Therefore the replacement nuts are somewhat narrower, but much thicker than current standards.

The replacement nuts have square ends, and the washers have parallel faces. There is therefore no facility to provide proper alignment in case the bearing faces are not parallel.

It is not known what tension was applied to the replacement bolts, but if it were the same as originally (90 tons), then the axial stress in the shank would be 477 N/mm^2. This provides 360 tons total tension, which should be greater than any applied load. The dead load tensions in the side and main span hangers are approximately 1525kN and 1050kN respectively, and it is clear that there is sufficient prestress to easily accommodate the external hanger loads.

Therefore, given that the same materials have been used as originally, plain nuts have been used and the prevailing stress is well below yield, we conclude that it is unlikely that the problem identified with the cable band nuts will occur with the hanger holding down bolts.

6.2 Back Stay Cable Band Bolts

These bolts are used in the small two bolt cable bands in the back stays and in the flanged cable bands adjacent to the cable sleeves. They are the originals and were not changed during the hanger replacement contract.

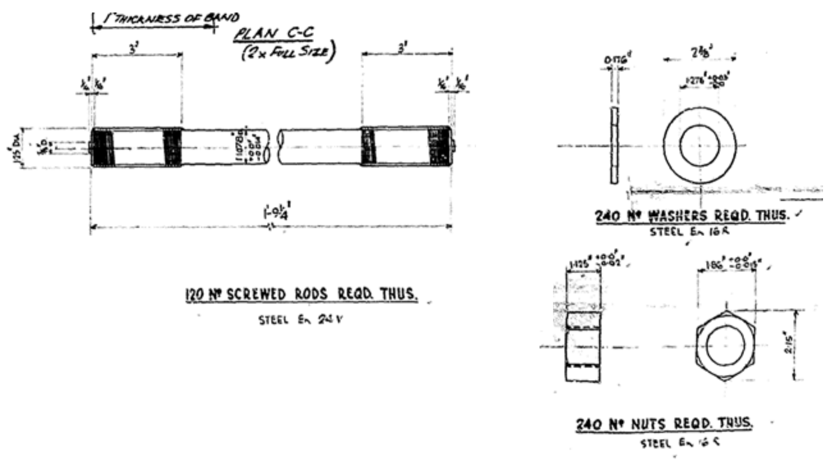


Fig 6.03: Back Stay Cable Band Bolts (ACD 2215)

The bolts are made from En24V steel and the nuts and washers from En16R. The nuts are of the plain pattern and not of the Roberts type.

There are no known problems with these bolts apart from some corrosion. Therefore we do not believe they will be subject to the same failure type as the replacement cable band nuts.

7 Conclusions and Recommendations

The following initial conclusions have been drawn from this investigation.

- Nine failed nuts have been discovered across the bridge on both cables and in all spans. (For some reason all failed nuts on the east cable were located in the north east side span.) Therefore the failures are not limited to a small area.
- All failed nuts were located on the live (jacking) side of the bolt, suggesting that the tensioning method or arrangement contributed significantly to the mode of failure.
- All of the nuts removed from the west cable exhibit a characteristic circumferential crack at the shoulder and vertical cracks in the hexagonal part. The east cable nuts appear to follow a similar pattern, hence the failures appear to have the same cause.
- It appears that there may have been some misalignment of the spherical washer assemblies that could lead to uneven loading in the nuts. This could be a significant factor, and further checks should be made on the east cable nuts prior to their replacement.
- Laboratory testing of the first failed nut recovered suggested that the circumferential crack was formed first, initiating at the re-entrant corner in a corrosion pit where the cadmium plating was missing. In this nut there were a number of initiation sites from which the circumferential crack grew. The vertical cracks followed later and were fibrous and ragged indicating overload.
- The laboratory testing confirmed that the steel material was within the specification, so that the cause of defective material could be ruled out.
- There was no evidence of hydrogen embrittlement resulting from the cadmium plating process.
- The steel used in the replacement nuts and bolts has a higher alloy content which has allowed heat treatment to achieve higher yield and tensile strengths than the original bolts. The replacement bolts have only slightly increased strength, but the strength of the nuts has increased significantly. The original bolts were matched with nuts that were much softer. It is possible that the use of a higher strength of steel for the nuts (with associated loss in ductility) could be a contributory factor.
- The dimensions of the new nuts and bolts closely replicate the originals, although the conversion from a $1^1/_2$ inch imperial bolt to a M39 metric bolt has resulted in the nuts having thinner sections than the originals.
- The dimensions of the new nuts are small in comparison with current standards for “normal” nuts. They are particularly small in comparison with nuts used on other suspension bridge cable band bolts. This, combined with the increase in bolt size outlined in the previous point, is likely to be significant.
- The method of tensioning has changed from that used during original construction. The original bolts were tightened by torque wrench, and the bolts were re-tensioned several times during construction as the load in the cable increased and its diameter reduced. Finally, all nuts were given an extra half turn to ensure the bolt was in the plastic zone. This allowed the redistribution of any moment arising from misalignment at ends.
- The replacement bolts were tensioned to the same nominal load (approx. 80 tons) using hydraulic tensioners. This load would keep the stress level below yield, i.e. within the elastic zone. The achieved tensions were assessed on the basis of a value of Young’s Modulus calculated for each bolt. The values of Young’s Modulus had a variation far in excess of what would be normally expected. Analysis of the calculation method used suggested the incorrect bolt length had been used in calculating the Young’s Modulus for each bolt. Reassessment of the tensions achieved using the conventional measured extension applied to a load/extension curve suggested a much wider variation than

thought by the designer. However, no excessive tensions were found. It was concluded that although the methodology used was flawed, it was unlikely to be detrimental to the bolts or nuts.

- Records of the tensions in the bolts with failed nuts were reviewed and it appeared that there was nothing exceptional. Installation dates were reviewed to check if the failed nuts fitted any pattern, however, none was found.

In summary, no single factor has been established as the cause of the failures. It would appear that there are a number of contributory factors including the misalignment of washers, poor coating in the re-entrant corner plus moisture ingress, use of a much higher grade of steel for the nuts with associated loss in ductility, and dimensional conversion from imperial to metric reducing the nut cross sections plus the nut size being small by modern standards.

The consequence of this conclusion is that, potentially, any nut could fail in this way. The first stage of crack initiation and growth in the circumferential direction cannot be observed without dismantling and the use of NDT is unlikely to be helpful. Therefore it is possible for other nuts to have this first stage cracking without our knowledge.

This leads to the inevitable conclusion that, for safety, all nuts should be replaced. An appropriate timescale for this would be the short to medium term. It may be possible to reuse the bolts, but this would depend of the design of the new nuts. Assuming that a somewhat larger nut would be employed, the overall length would need checked to see if it were still adequate. Also, if the nut were to have a larger fillet radius, then new washers might be required. However, before any action plan for wholesale replacement is put into place the following should be carried out.

- Replace the five failed nuts on the east cable, and examine the failures to confirm their similarity.
- One nut should be sent to ESRT for examination and further confirmation of the above.
- Prior to replacement of the five failed nuts, the verticality of the washer faces should be measured. It would be useful to carry out spot checks on other washers with unfailed nuts to establish if this is a significant factor.

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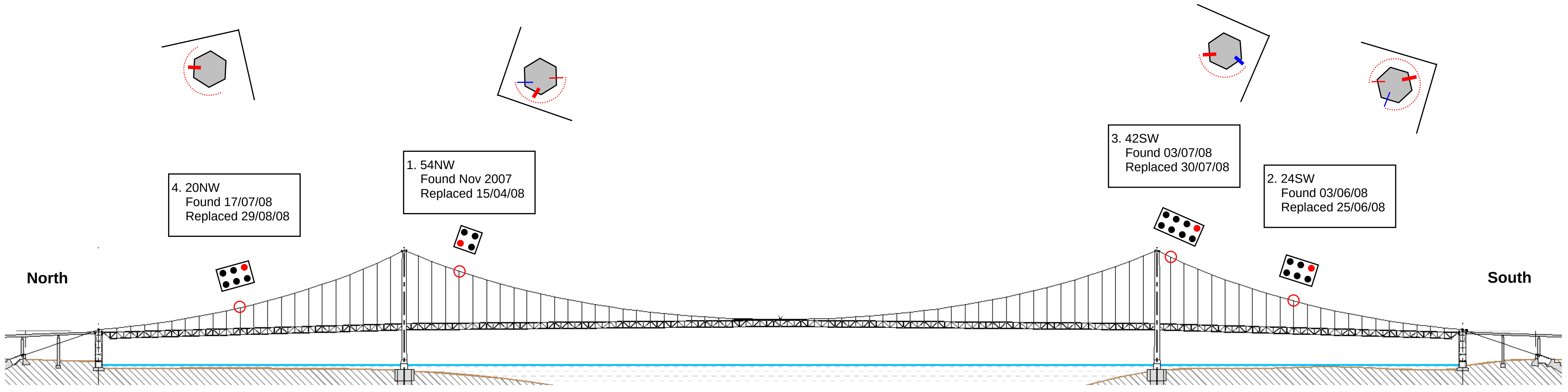
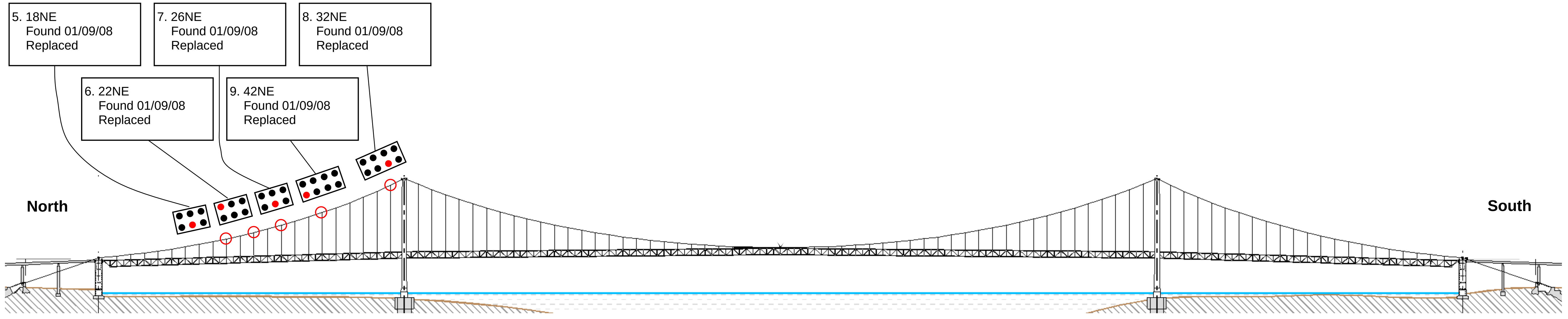
Appendices

Appendix 1 – Location of Broken Nuts



West Cable



East Cable

Appendix B – Specification for Replacement Bolts

APPENDIX 1/72 : Construction Constraints - Cable Band Bolt Replacement

The Contractor shall replace the existing cable band bolts in accordance with the following constraints.

1. **General**

    a) The Contractor shall provide and maintain all necessary temporary works to ensure that the wrapping to the main cable is left undisturbed and undamaged by the operations to replace the existing cable band bolts.

2. **Removal of Existing Bolts**

    a) The details of the existing cable band castings and bolts can be found on the original fabrication drawings listed in Appendix 0/6 of this specification. The Contractor should note that the original protective system includes cadmium plating.

    b) The removal of the existing cable band bolts shall be carried out with the load from the hanger removed.

    c) The existing bolts shall be de-tensioned and removed for replacement in accordance with the sequence shown on drawing 33111/B/20. Each bolt shall be de-tensioned by rotating the nut by a half turn. No application of heat or burning of the bolts shall be permitted.

    d) At no time shall more than 2 No. bolts be fully de-tensioned or removed from a cable band.

    e) The Contractor shall provide and maintain all necessary temporary works to ensure the cable band remains in its original position throughout the replacement of the bolts. Welding, heating or burning of the cable bands shall not be permitted.

3. **Installation of New Bolts**

    a) Before the installation of the new bolt the Contractor shall ensure the existing holes in the cable band casting are clean and free from any grease or debris. Immediately before the installation of the new bolts the Contractor shall spray the internal surfaces of the bolt holes and any other accessible areas of the cable band casting with a rust inhibitor as described in Appendix 19/1 of this Specification.

    b) Where required to allow the installation of the new bolt the existing holes in the casting may be reamed out to a maximum diameter of 41mm. Reaming of the existing holes shall only be undertaken with the approval of the Engineer.

    c) The new bolts shall be installed in the sequence shown on drawing 33111/B/20 and stressed in pairs to their initial load as defined in table 1/72/1. On completion of the initial sequence of replacement all bolts shall simultaneously be stressed to their final load as defined in Table 1/72/1. Stressing of the bolts shall be carried out hydraulically in direct tension (i.e. by bolt tensioner or similar device).

d) Prior to applying any load the length of each bolt shall be accurately measured and recorded. On completion of the initial sequence of replacement each bolt shall be measured again to verify the load in the bolt. This shall be repeated after the final stage of loading and the bolt load adjusted accordingly to correct for any inaccuracies which may have occurred. All measurements shall be temperature corrected.

e) The final stressing of the bolts in the cable band shall be carried out simultaneously with a maximum load differential during loading of 5% between any 2 No. bolts in the group. Final load tolerances shall be as stated in Table 1/72/1.

f) On completion of the initial bolt installation the Contractor shall rake out and replace the existing sealant between the two halves of the cable band casting.

i) The joint sealant shall be Fosroc Silicone Sealant 33, complying with BS 5889 Type B , or an approved equivalent. The joint shall be prepared and the sealant applied in accordance with the manufacturer's current data sheet and instructions.

ii) The Contractor shall ensure that any cleaning fluid used to degrease the joint surfaces is not spilled or applied to the bolt socket chamber or the main cable surface.

iii) The Contractor's proposals for cleaning and sealing the joint shall be compatable with the adjacent protective coatings and shall be submitted to the Engineer for approval a minimum of four weeks prior to inclusion in the Works.

Table 1/72/1

Stage	Bolt Load	Tolerance
Initial	200 kN	+/- 5%
Final	910 kN	$+2^1/_2\%$, -0%
Maximum Load During Tensioning	955 kN	+0%

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APPENDIX 1/73 : Specification for Replacement Bolts

The following specification applies to the replacement bolts for the cable bands and the anchorage brackets.

Manufacture of Bolts

1. All components for the replacement bolts shall be manufactured from bright steel complying with BS 970 : Part 3 : 1991 and to the following grades of steel :

Cable Band Bolts	Threaded Rod	Grade 826M40X
	Nuts and Washers	Grade 826M40W
	End Caps	Grade 080M40
Anchorage Bracket Bolts	Threaded Rod	Grade 817M40V
	Nuts and Washers	Grade 605M36R
	End Caps	Grade 080M40

<u>All the mechanical properties tabulated in BS 970 : Part 3 : 1991, including the minimum 0.2% Proof ~~Test~~, shall be met by the various steels used in the manufacture of these components.</u> Stress

Steel used to manufacture the threaded rod shall be precision ground bar in accordance with BS 970 : Part 3 : 1991, Clause 2.1.3. The tolerance for precision ground bar shall be Class B as defined in Table 3 of BS 970 : Part 3 : 1991.

2. The threads on the replacement cable band bolts shall be ISO Metric Screw Threads <u>M39</u> x 3 to BS 3643 : Part 1 1981, with medium fit (6H/6g) to BS 3643 : Part 2 : 1981. Dimensional tolerances shall be checked by the Contractor by using a gauging system which complies with BS 919 : Part 3.

The threads on the replacement anchorage bracket bolts shall be ISO Metric Screw Threads M56 x 4 to BS 3643 : Part 1 1981, with medium fit (6H/6g) to BS 3643 : Part 2 : 1981. Dimensional tolerances shall be checked by the Contractor by using a gauging system which complies with BS 919 : Part 3.

The threads for the rods shall be rolled threads with the nuts and end caps being single point screw cut threads. The requirements for dimensional tolerances of the threads shall be met after the application of the protective coating. The extent of the threads shall be as shown on drawings 33111/B/12 and 33111/B/21.

3. Certification giving details of chemical analysis and mechanical properties for all steel used in the manufacture of the bolts shall be provided by the Contractor. All materials used in the production of the individual bolts shall be fully traceable at all stages of the manufacturing process with a full record being provided by the Contractor to the Engineer prior to the installation of the bolts in the Works.

4. Each bolt shall have a unique identification number with the history of its manufacture and loading being recorded. The identification shall be hard stamped or engraved on the bolt in the location shown on drawings. The identification number shall be applied before the application of the protective coating.

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5. Threaded rods shall have a factory applied protective coating of cadmium plating with a chromate conversion coating on top in accordance with BS 1706:1990 classification code Fe/Cd 25 c 2C. The minimum thickness of cadmium plating coating shall be 25 microns. Any process required to prepare the steel surface prior to plating shall be agreed with the Engineer a minimum of four weeks prior to commencement of the works. Pickling processes will not be allowed.

6. All nuts, washers and end caps for both the Cable Band Bolts and the Anchorage Bracket Bolts shall have a factory applied protective coating of cadmium plating, with no conversion coating, in accordance with BS 1706:1990 classification code Fe/Cd 25. The minimum thickness of cadmium plating coating shall be 25 microns. Any process required to prepare the steel surface prior to plating shall be agreed with the Engineer a minimum of four weeks prior to commencement of the works. Pickling processes will not be allowed.

7. All plated components shall be free from visible defects such as unplated areas, blisters and nodules. The surface of all nuts, washers and end caps shall be suitable for application of a protective paint system as detailed in Appendix 19/1.

8. The Contractor shall take due account of the material properties of each component before applying the heat treatment specified in Clause 9 below. The Tensile Strength in accordance with BS 970: Part 3: 1991 is as follows:

Tensile Strength (N/mm^2)

Cable Band Bolts	Threaded Rod	1150-1300
	Nuts and Washers	1075-1225
	End Caps	625-725
Anchorage Bracket Bolts	Threaded Rod	1000-1150
	Nuts and Washers	700-850
	End Caps	625-775

9. Before and after the application of the cadmium plating the bolts shall be heat treated as follows:

a) Threaded rods, nuts, washers and end caps shall be heat treated before cadmium plating for a minimum of 3 hours at a temperature range of 190°C to 220°C. The duration of heat treatment shall be measured from the time that all items in the oven have attained the specified temperature.

b) Threaded rods, nuts, washers and end caps shall be heat treated immediately after cadmium plating to relieve hydrogen embrittlement for a minimum of 24 hours at a temperature range of 190°C to 220°C. The duration of heat treatment shall be measured from the time that all items in the oven have attained the specified temperature.

c) The Contractor shall record and provide a chart for each complete bolt assembly (i.e. the threaded rod, nuts, washers, and end caps) plotting the temperature of each item against time for both heat treatment processes. This information shall be passed to the Engineer a minimum of four weeks before the bolt is installed in the Works.

d) The post-coating heat treatment shall be carried out prior to the application of the chromate conversion coating.

FORTH ROAD BRIDGE JOINT BOARD

10. Details of the bolts assemblies are shown on contract drawings 33111/B/12 and 33111/B/21.

11. The Contractor's manufacturing processes for all the components of the replacement bolts shall be compatible with the heat treatment specified in Clause 9 above. The Contractor shall ensure that the properties of the steel are not adversely affected by the heat treatment referred to in Clause 9 above.

12. The Contractor shall ensure that components manufactured from tempered steel are not heated above a temperature of 50°C below the tempering temperature.

13. The Contractor shall ensure that the steel properties produced during the manufacturing processes for all the bolts are consistent throughout the length of the bolt.

14. The Contractor shall undertake impact tests using either the Charpy test method or the Izod test method as approved by the Engineer. The frequency of the testing shall be as shown in Table 1/73/1. The Contractor shall submit his proposals for impact testing to the Engineer for approval a minimum of four weeks prior to commencing the tests. The test samples shall meet the following requirements:

    a) Charpy value: 28 Joules min. at a temperature of -20°C.

    b) Izod value: 34 Joules min. at a temperature of -20°C.

Testing of Bolts

1. The Contractor shall manufacture and undertake impact tests and tensile tests to failure of 10 No. of each size of replacement bolt as stated in Table 1/73/1. The bolts tensile tested shall be fully assembled with their washers and nuts. The threaded rods, nuts and washers forming the bolt shall be cadmium plated and fully heat treated in accordance with this specification. The samples for the impact tests shall be taken from the fully treated threaded rods under the length dimensioned 'B' in Figure 1/73/1 unless otherwise approved by the Engineer. No bolts for inclusion in the Works shall be manufactured (including the production of the steel) until the results of these tests have been approved by the Engineer in writing. The object of the tensile tests is to establish the stress/strain curves for the bolts in order that the load induced in the bolt on-site can be verified by measurement of their length. The tensile tests shall be carried out with the bolts at a constant temperature with 7 No. tests being undertaken at 20°C and the other 3 No. bolts being tested at -20°C as stated in Table 1/73/1.

2. In addition to the above tests the Contractor shall undertake at his own expense 1 No. additional impact test and tensile test of the complete bolt assembly for each separate production run of either the threaded rods or nuts. The properties of the bolt shall be the same as the bolts in the approved tests in item 1 above. The test results shall be passed to the Engineer a minimum of four weeks before the inclusion of the bolts from this production run in the Works.

3. The Engineer shall select at random additional bolts for impact testing and tensile testing. The number of bolts selected for this purpose shall be as stated in Table 1/73/1. The Contractor shall arrange to have the bolts tested on an individual basis at the same laboratory as the original bolt testing with the results being passed to the Engineer. The bolts tested shall have the same properties as the original test bolts.

4. Should any of the additional bolts tested in the opinion of the Engineer fail to meet the required standard the production run shall be discarded unless further tests prove to the satisfaction of the Engineer that the bolts in the particular production run are satisfactory for inclusion in the Works. The cost of all additional tests and the production of all replacement bolts shall be borne by the Contractor.

5. In addition to the impact tests and tensile tests on the bolts, a minimum of 5 No. nuts for each bolt diameter shall be proof load tested in accordance with BS EN 20898-6 : 1992 Clause 8.1. The nuts to be tested shall be cadmium plated and fully heat treated in accordance with this specification. No bolts for inclusion in the Works shall be manufactured (including the production of the steel) until the results of these tests have been approved by the Engineer in writing.

6. Testing shall be carried out to confirm the thickness of cadmium plating and chromate coating on each item of the bolt assembly. The Contractor shall test the threaded rods, nuts washers and end caps in accordance with Clause 8 of BS 1706:1990.

   The Contractor shall test a minimum of 1% of the total number of each item with samples being selected from throughout the production run. Where the rods, etc. are coated in batches a representative sample shall be tested from each batch unless otherwise agreed by the Engineer.

   Where test samples fail to meet the specified coating thickness further samples shall be tested to prove to the satisfaction of the Engineer that the items are satisfactory for inclusion in the Works. Where after further testing items continue to fail to meet the specification the whole batch of components shall be discarded and replaced by new components at the Contractor's expense.

   Individual test samples which fail to meet the specification shall be replaced at the Contractor's expense unless otherwise agreed by the Engineer.

   The Contractor is permitted to use sacrificial pieces of similar material and size to the component in question to fulfil the testing requirements for the chromate coating provided the sacrificial piece has undergone the same coating and heat treatment.

7. General testing of the materials used to manufacture the bolts shall be in accordance with BS 970 : Part 3 : 1991.

8. The Contractor shall submit a method statement and a detailed schedule for all the inspection and testing of the bolt components required by this Specification for the approval of the Engineer a minimum of four weeks prior to the testing commencing. The Contractor shall inform the Engineer of the date the testing will be undertaken a minimum of one week before the tests are undertaken and arrange access for the Engineer or his representatives to witness the tests All laboratories carrying out testing shall have a NAMAS accreditation.

9. The Contractor shall ensure that all testing is completed and certificates of compliance with the requirements are provided to the Engineer for approval a minimum of one week prior to any bolt assembly being included in the Works. No bolt or component shall be included in the Works without the full certification and the written approval of the Engineer.

Appendix 1/73 continues on additional page: Page 3.61A

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10. The Contractor shall undertake a Hardness Test by a method approved by the Engineer on both ends of each fully manufactured threaded rod immediately prior to the pre-coating heat treatment for the cadmium plating, referred to in Clause 9. above. The Contractor shall ensure that his proposed method of Hardness Testing has no detrimental effects on the properties of the threaded rod and shall submit his proposals for testing to the Engineer for approval a minimum of four weeks prior to the tests commencing.

Table 1/73/1

Test	Cable Band Bolts	Anchorage Bracket Bolts
Initial Tensile Test	7 No. @ 20°C 3 No. @ -20°C	7 No. @ 20°C 3 No. @ -20°C
Initial Impact Test	10 No.	10 No.
Additional Tensile Test	25 No. @ 20°C	20 No. @ 20°C
Additional Impact Test	25 No.	20 No.
Production Run Tensile Test	1 No. per run @ 20°C	1 No. per run @ 20°C
Production Run Impact Test	1 No. per run	1 No. per run
Nut proof Load Test	5 No.	5 No.
Protective Coating Test	Min. 1% or one sample per batch, whichever is greater	Min. 1% or one sample per batch, whichever is greater

General

10. In addition to the bolts for testing and inclusion in the Works the Contractor shall manufacture and deliver to the Forth Road Bridge Joint Board additional spare bolts as detailed in the Bill of Quantities for future use.

11. All bolts shall be packaged, stored, handled and transported in such a manner that the protective coating shall remain clean and undamaged. Bolts with damaged protective coatings shall be replaced or the coatings made good to the satisfaction of the Engineer by the Contractor at no cost to the Client.

Measurement of Cable Band Bolt Length

1. The Contractor shall design and manufacture a calliper to measure the length of the cable band bolts during the loading of the bolt as described in Clause 3 (d) of Appendix 1/72

2. The callipers shall be designed to be operated by hand by a single person.

3. The callipers shall measure the length of the bolt to an accuracy of +/-0.025mm.

4. Measurements shall be taken over the full length of the bolt and over the unloaded length, Dimensions A and B in Fig. 1/73/1 respectively, in order that the actual load in the bolt may be calculated. All measurements require to be temperature corrected and the callipers shall be designed in such a manner that they can be calibrated to allow for temperature correction.

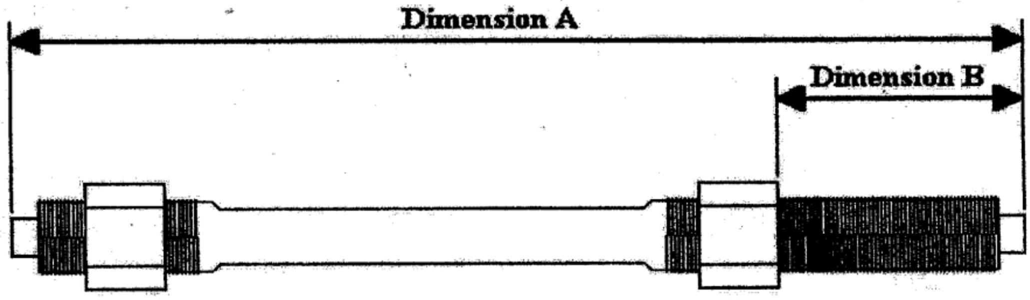


Fig. 1/73/1

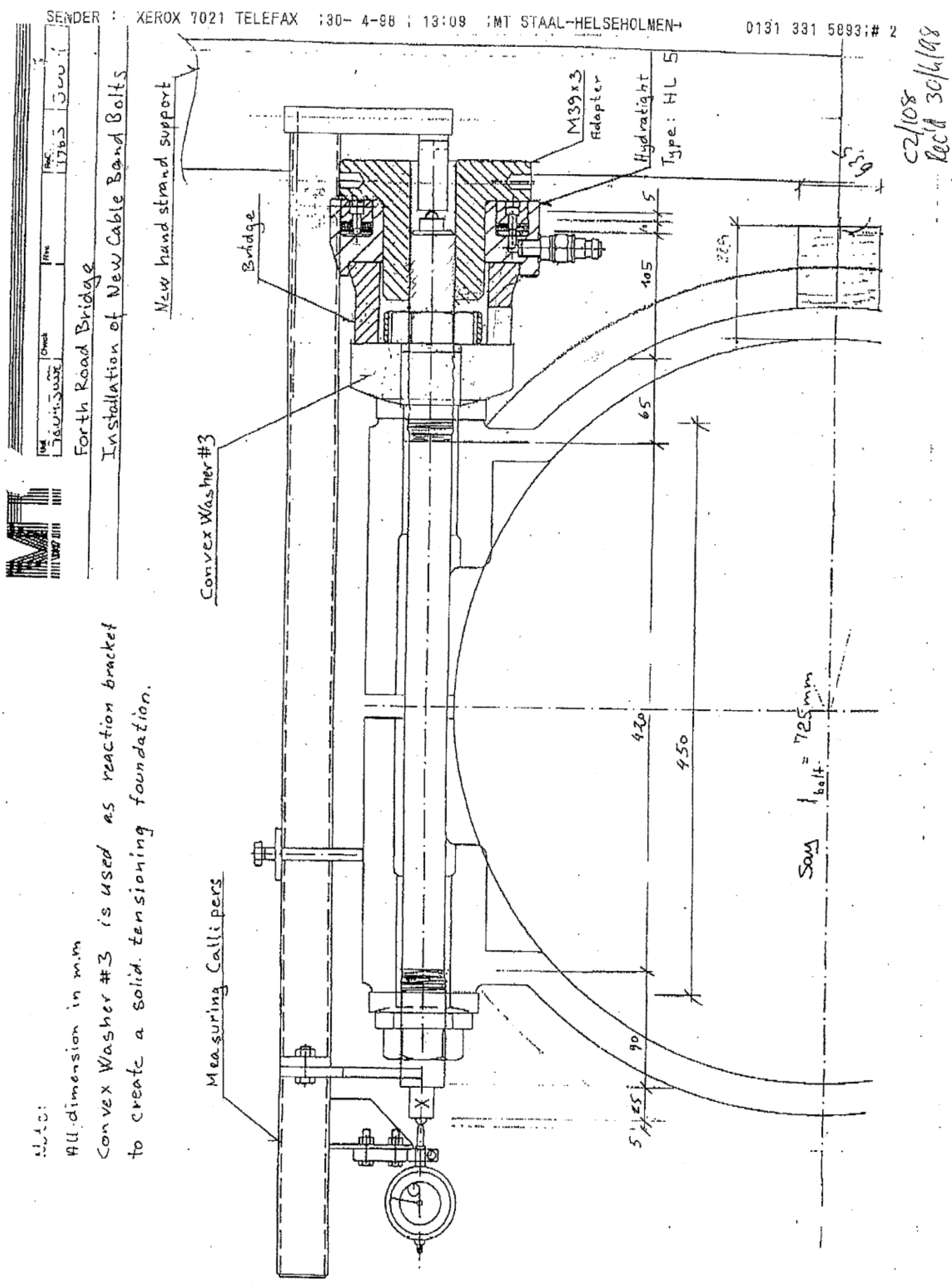
5. Details of the Contractor's proposals for the calliper are to be submitted to the Engineer for approval a minimum of four weeks before the callipers are manufactured. Approval of the design and fabrication drawings shall be in accordance with Series 100 Clause 106.4 of the Specification.

6. The Contractor shall provide 1 No. calliper to the Engineer for the duration of the contract with a further two unused callipers being provided to the Forth Road Bridge upon practical completion of the contract. Callipers for the Contractor's own use during the Works shall be considered as Contractor's plant and shall be manufactured at the Contractor's own cost.

7. The Contractor shall maintain all callipers provided for the duration of the Contract.

8. Full operating and maintenance manuals shall be issued with the callipers provided to the Forth Road Bridge Joint Board.

Appendix C – M&T Bolt Installation Method Statement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Forth Road Bridge
Installation of New Cable Band Bolts
New hand strand support
Bridge
M39x3
Adapter
Hydratight
Type: HL 5
5
105
65
420
450
90
25
5
Convex Washer #3
Say l_{bolt} = 725mm
C2/108
Rec'd 30/4/98
All dimension in m.m
Convex Washer #3 is used as reaction bracket
to create a solid tensioning foundation.
Measuring Callipers

LC to CT 4\5\07.

CR/2290 25/8/99.

Forth Road Bridge Ref. 1963

Both this and revision 9 acceptable

Doc. No. 1.722 Work Instruction-New Cable Band Bolts

Purpose of Operation:	Remove old bolts clean and possibly ream holes and install new bolts in the cable bands.
Location:	Cable band various panel points.
	Cable band bolts A and B are the lowest set of bolts in a cable band.
Crew:	2 riggers.
Tools And Equipment:	Tentec hydraulic bolt tensioners, Tentec hydraulic power pack (in drip trays ~~on the footpath~~), revel reamer, slide calliper and Hydratight bolt scanner.
Risk Assessments: Doc. no.0.005	RI 1 Lifting of material with Hiab crane from a Lorry. RI 3 Worker activity on the footway / cycle path. RI 4 Worker activity on the scaffolding. RI 5 Operating hydraulic equipment. RI 6 Handling of cadmium plated bolts. RI 7 Lifting of material with the Minifor winch. RI 11 Painting. RI 18 Workers activities in working platform at main cable. RI 19 Working at night time.
Preparations/ Mobilisation:	New bolts is painted according to: Paint instruction. Area H, 09.05.99., enclosure II. New bolts are batches in set for each panel point in compound and reference length is measured with Hydratigth scanner. A record on paper will be made, Doc. No. 50.022, enclosure I.

Sequence of Operation:

1. Adjust the safety relief valve on the Tentec Booster to a **maximum pressure of 1200 bar** (850kN). Measured by the gauge.
2. Cable band bolts are de-tensioned one half turn of the nut with the Tentec equipment, following the sequence on pages 3 to 5.
3. Fully release and remove bolt C and D.
4. The bolt holes will be cleaned of grease and debris and, if necessary, reamed to a maximum 41mm as required. (The reamer will be adjusted by a sliding calliper or equivalent).
5. The bolt holes will be painted with **first coat of primer:**
   Copon Polycote Aluminium Primer, 50 microns.
   Paint instruction. Area L, 07.05.99., enclosure III.
6. First coat shall dry two hours, before applying **second coat of primer** in C and D holes:

Title					
	33111 Forth Road Bridge	made by		Doc.no./rev	1.722-10
	Hanger Replacement	Check		Date	24-08-99
	New Cable Band Bolts-Work Instructions	App..		Page / of	1/5

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Forth Road Bridge — no comment. — Ref. 1963

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Doc. No. 1.722 Work Instruction-New Cable Band Bolts

Purpose of Operation:	Remove old bolts clean and possibly ream holes and install new bolts in the cable bands.
Location:	Cable band various panel points.
	Cable band bolts A and B are the lowest set of bolts in a cable band.
Crew:	2 riggers.
Tools And Equipment:	Tentec hydraulic bolt tensioners, Tentec hydraulic power pack (in drip trays on the footpath), revel reamer, slide calliper and Hydratight bolt scanner.
Safety:	Handling of cadmium plating, work on scaffolding, use of hydraulic equipment and paint.
Preparations/ Mobilisation:	New bolts is painted according to: Paint instruction. Area H, 09.05.99., enclosure II. New bolts are batches in set for each panel point in compound and reference length is measured with Hydratigth scanner. A record on paper will be made, Doc. No. 50.022, enclosure I.

Sequence of Operation:

1. Adjust the safety relief valve on the Tentec Booster to a **maximum pressure of 1200 bar** (850 kN). Measured by the gauge.
2. The old cable band bolts are de-tensioned one half turn of the nut with the Tentec equipment, following the sequence on pages 3 to 5.
3. Fully release and remove bolt C and D.
4. The bolt holes will be cleaned of grease and debris and, if necessary, reamed to a maximum 41mm as required. (The reamer will be adjusted by a sliding calliper or equivalent).
5. The bolt holes will be painted with **first coat of primer**:
   Copon Polycote Aluminium Primer, 50 microns.
   Paint instruction. Area L, 07.05.99., enclosure III.
6. First coat shall dry two hours, before applying **second coat of primer** in C and D holes:
   Copon Polycote Aluminium Primer, 50 microns.
   Paint instruction. Area L, 07.05.99., enclosure III.

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		Check	BSM	Date	03-06-99
		App..	BSM	Page / of	1/5

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7. The new cable band bolts C and D, can be installed as soon as the second coat of primer is touch dry.
   Installed according to drawing no. 1.804, enclosure IV.

   The spherical washer, thread and nut shall be lubricated with Thread-Eze.

8. The new cable band bolts are installed in the cable band with a distance from the end of the thread to the end of the nut equal to <u>20 mm</u> (at the end with 90 mm thread) and tensioned in pairs by the Tentec bolt tensioners to an initial load as defined 300 bar (approx. 200 kN).

9. Repeat step 3-8 for each pair of cable band bolts in the sequence described on pages 3 to 5.

10. Before any further tensioning of cable band bolts, application of primer and sealant in the cable band top joint has to be carried out according to WI. 1.723.

11. Tentec bolt tensioners are installed on all cable band bolts for final tensioning of all bolts simultaneous.
    The pressure is raised to **1150 bar (812 kN)**.

12. The bolt number, the bolt temperature, panel point and position in the cable band will be recorded.

13. The elongation is measured with the Hydratight bolt scanner on all bolts and the measurement recorded on paper, including the reading of the hydraulic pressure.
    The corrected "E"- value of the bolts is calculated and recorded on enclosure doc. no. 50.022.

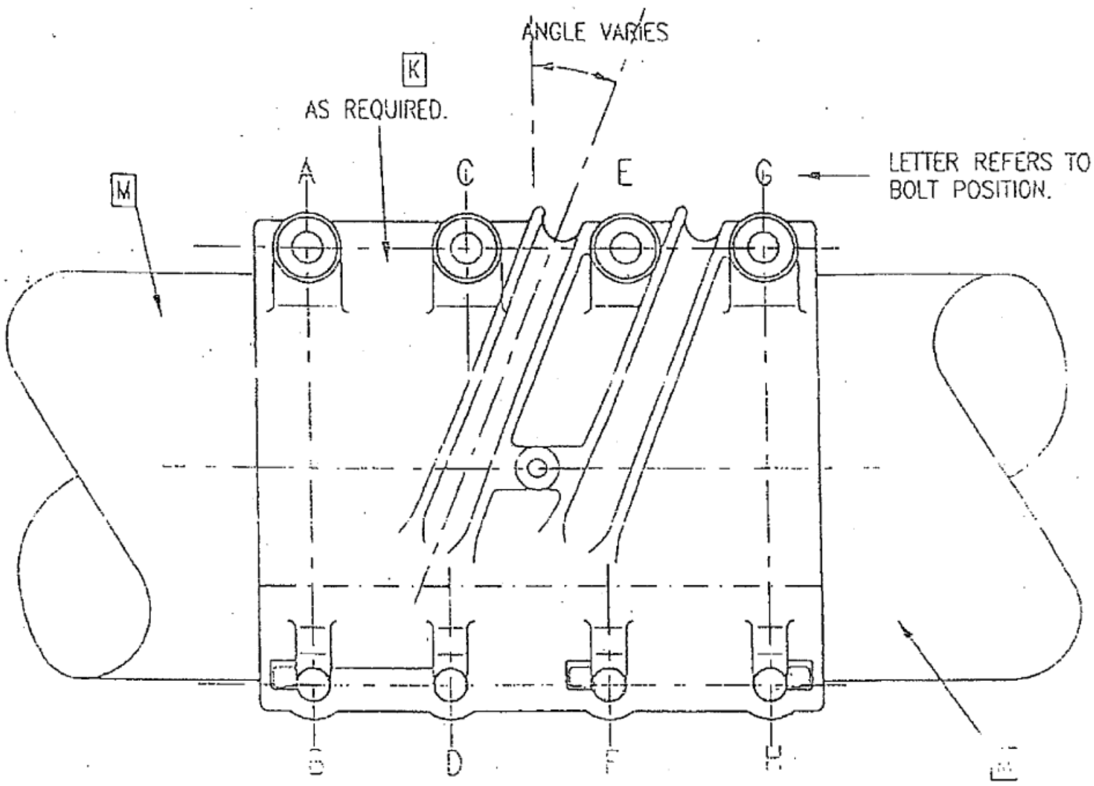
14. All nuts are uniformly tightened by hand and the pressure is released.

15. The elongation for each bolt is measured with the Hydratight bolt scanner and recorded on enclosure doc. no. 50.022.

16. The corrected force in each bolt is calculated from the "E"- value obtain in 13 and recorded on enclosure doc. no. 50.022.

17. If corrected force in any bolt is below 750 kN, the Engineer will confirm whether to raise the pressure on all bolts to a suitable level, **maximum 1200 bar** (850 **kN**) and point 12 to 16 repeated.

18. This Work Instruction is written for cable band with 4 bolts.
A similar method is used for 6 and 8 bolts - following the sequence on page 3-5.



CABLE BAND # 1

Cable band bolt A and B are the lowest set of bolts in a cable band.

REPLACEMENT SEQUENCE FOR BOLTS IN CABLE BAND # 1

1. DE-TENSION EACH BOLT BY ONE HALF TURN IN THE SEQUENCE OF C, D, E, F, A, B, G, H.
2. FULLY RELEASE AND REMOVE BOLTS C AND D.
3. AFTER TREATMENT OF BOLT HOLE INSTALL NEW BOLTS IN LOCATIONS C AND D AND TENSION TO INITIAL SET (200 KN) IN ACCORDANCE WITH THE SPECIFICATION.
4. REPEAT STEPS 2 AND 3 FOR LOCATIONS E AND F.
5. REPEAT STEPS 2 AND 3 FOR LOCATIONS A AND B.
6. REPEAT STEPS 2 AND 3 FOR LOCATIONS G AND H.
7. FULLY TENSION ALL BOLTS IN ACCORDANCE WITH THE SPECIFICATION.

Title	33111 Forth Road Bridge	made by	SSR	Doc.no./rev	1.723-9
	Hanger Replacement	Check	BGM	Date	03-06-99
	New Cable Band Bolts-Work Instructions	App..	BGM	Page / of	3/5

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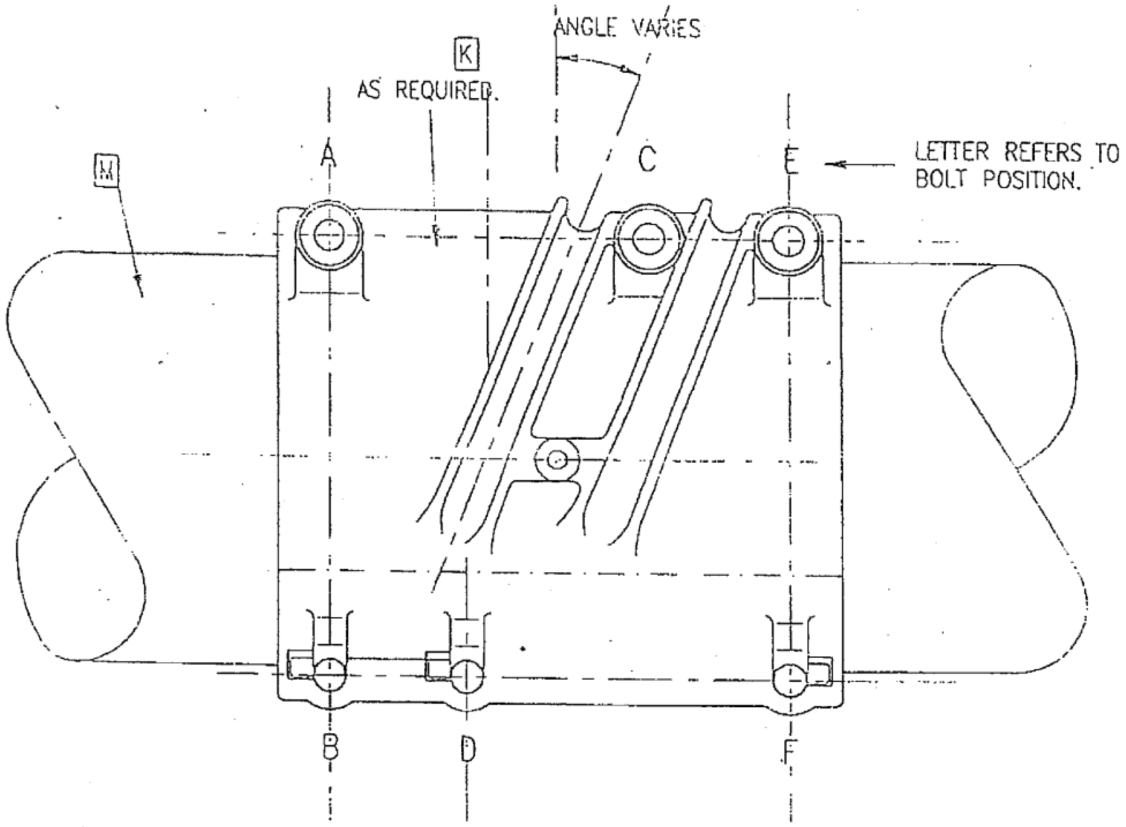
Forth Road Bridge Ref. 1963



CABLE BAND # 2

Cable band bolt A and B are the lowest set of bolts in a cable band.

REPLACEMENT SEQUENCE FOR BOLTS IN CABLE BAND # 2

1. DE-TENSION EACH BOLT BY ONE HALF TURN IN THE SEQUENCE OF C, D, B, A, E, F.
2. FULLY RELEASE AND REMOVE BOLTS C AND D.
3. AFTER TREATMENT OF BOLT HOLE INSTALL NEW BOLTS IN LOCATIONS C AND D AND TENSION TO INITIAL SET (200 KN) IN ACCORDANCE WITH THE SPECIFICATION.
4. REPEAT STEPS 2 AND 3 FOR LOCATIONS A AND B.
5. REPEAT STEPS 2 AND 3 FOR LOCATIONS E AND F.
6. FULLY TENSION ALL BOLTS IN ACCORDANCE WITH THE SPECIFICATION.

Title	33111 Forth Road Bridge Hanger Replacement **New Cable Band Bolts-Work Instructions**	made by	SSR	Doc.no./rev	1.722-9
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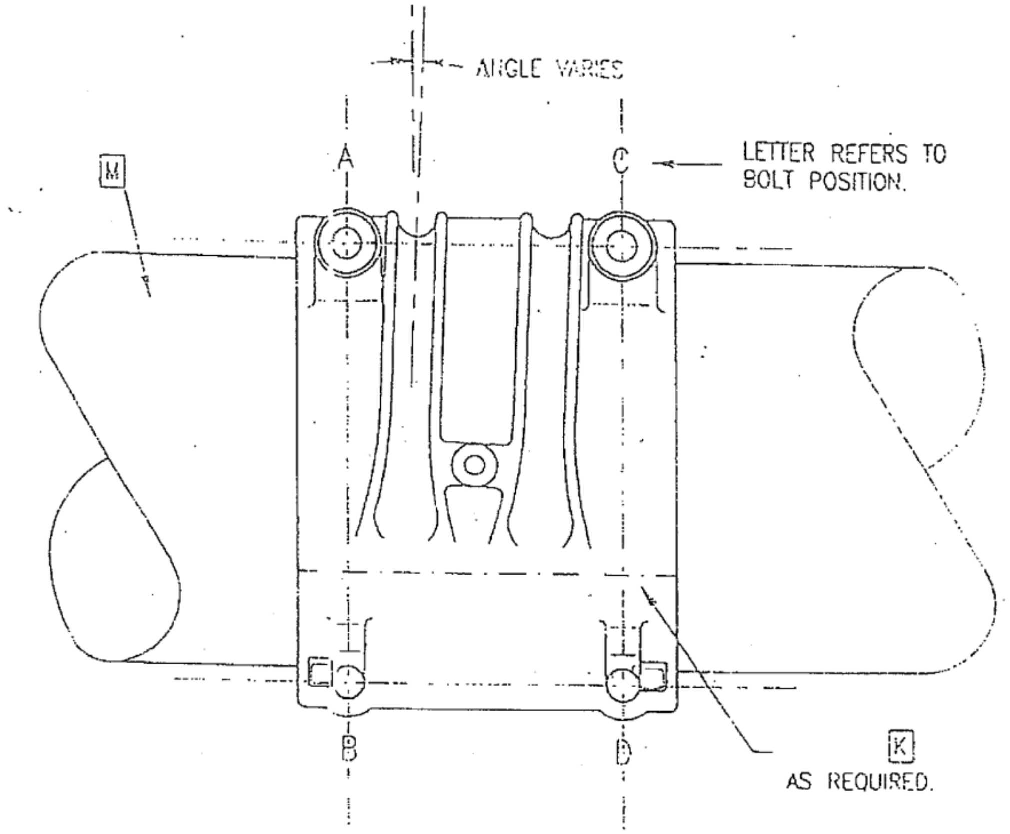

CABLE BAND # 3

Cable band bolt A and B are the lowest set of bolts in a cable band.

REPLACEMENT SEQUENCE FOR BOLTS IN CABLE BAND # 3

1. DE-TENSION EACH BOLT BY ONE HALF TURN IN THE SEQUENCE OF A, B, C, D.
2. FULLY RELEASE AND REMOVE BOLTS C AND D.
3. AFTER TREATMENT OF BOLT HOLE INSTALL NEW BOLTS IN LOCATIONS C AND D AND TENSION TO INITIAL SET (200 KN) IN ACCORDANCE WITH THE SPECIFICATION.
4. REPEAT STEPS 2 AND 3 FOR LOCATIONS A AND B.
5. FULLY TENSION ALL BOLTS IN ACCORDANCE WITH THE SPECIFICATION.

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	Hanger Replacement	Check	[illegible]	Date	03-06-99
	New Cable Band Bolts-Work Instructions	App..	[illegible]	Page / of	5/5

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(I)

MONBERG & THORSEN

Doc. No. 50.022-04, Date 27.05.99

CABLE BAND BOLTS

Panel Point

Sheet No. 1

BOLTS *X - mark actual position*	A C E G / B D F H	A C E G / B D F H	A C E G / B D F H	A C E G / B D F H

Cable band bolt A and B are the lowest set of bolts in a cableband

BOLT SCANNER No.	BS			
Bolt Group	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Bolt no.				
THREADED ROD, ID No.	RA C	RA C	RA C	RA C
Nut, short end, ID No.	RA CN	RA CN	RA CN	RA CN
Nut, long end, ID No.	RA CN	RA CN	RA CN	RA CN
Date		Time		
Temparature °C *				
Gain value				
Length L-REF mm				
Initials, Supervisor				
INITIAL TENSIONING				
Pressure bar	300 - 320	300 - 320	300 - 320	300 - 320

DURING TENSIONING ***Max pressure 1200 bar***

Date		Time		
Temparature °C *				
Pressure bar (1150)			* to be mesured in shadow	
Scanner readings:				
Gain value				
Elongation mm				

INSTALLATION

Scanner readings:				
Gain value				
Force kN				
Elongation mm				
Initials, Supervisor				