METAL FATIGUE OF MEMBRANE PLATE CONNECTIONS

An Installers Case Study

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1. INTRODUCTION

This paper addresses the causes of the fatigue failure of a membrane plate U–Bolt.

Highlighting:

- The need for greater control at installation.
- The requirement for increased articulation of membrane plates to accommodate for installation tolerances and time dependant factors such as connection detail movement or fabric tension reduction.

2. CASE STUDY

2.1 SCOPE OF PROJECT

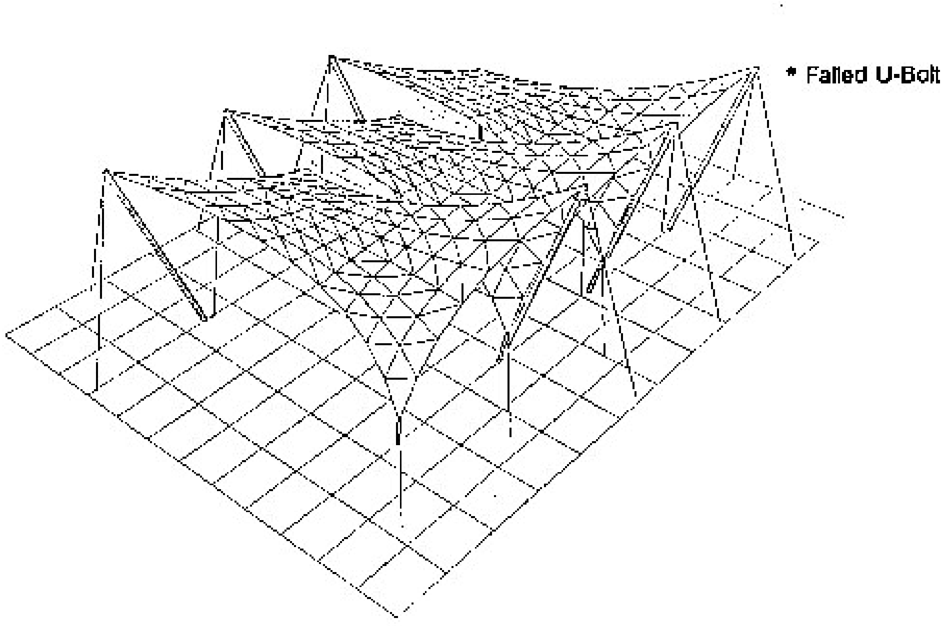


FIGURE A

Structure Type = Hypar

Fabric Type = Type II – P.V.C coated, with Polyester Base Fabric

Fabric Prestress = 2KN/m

Guy Cables = 28ϕ 1 x 19 Galvanised with rigging screws

Catenary Cables = 18ϕ 1 x 19 Galvanised with swaged stud ends

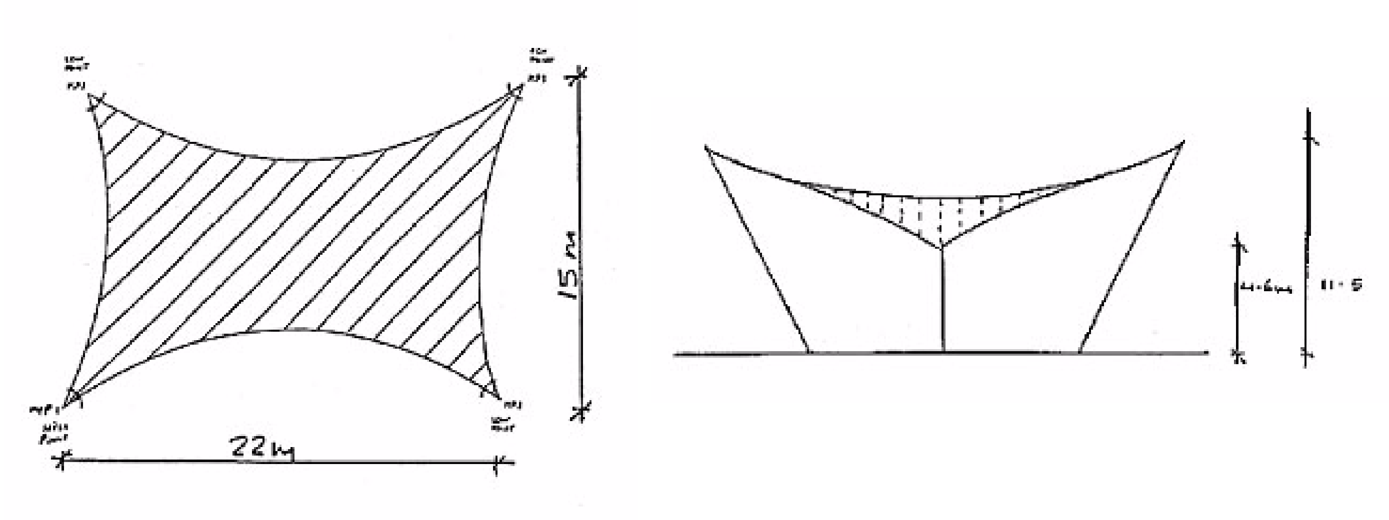


FIGURE B

2.3 *MEMBRANE PLATE DESIGN*

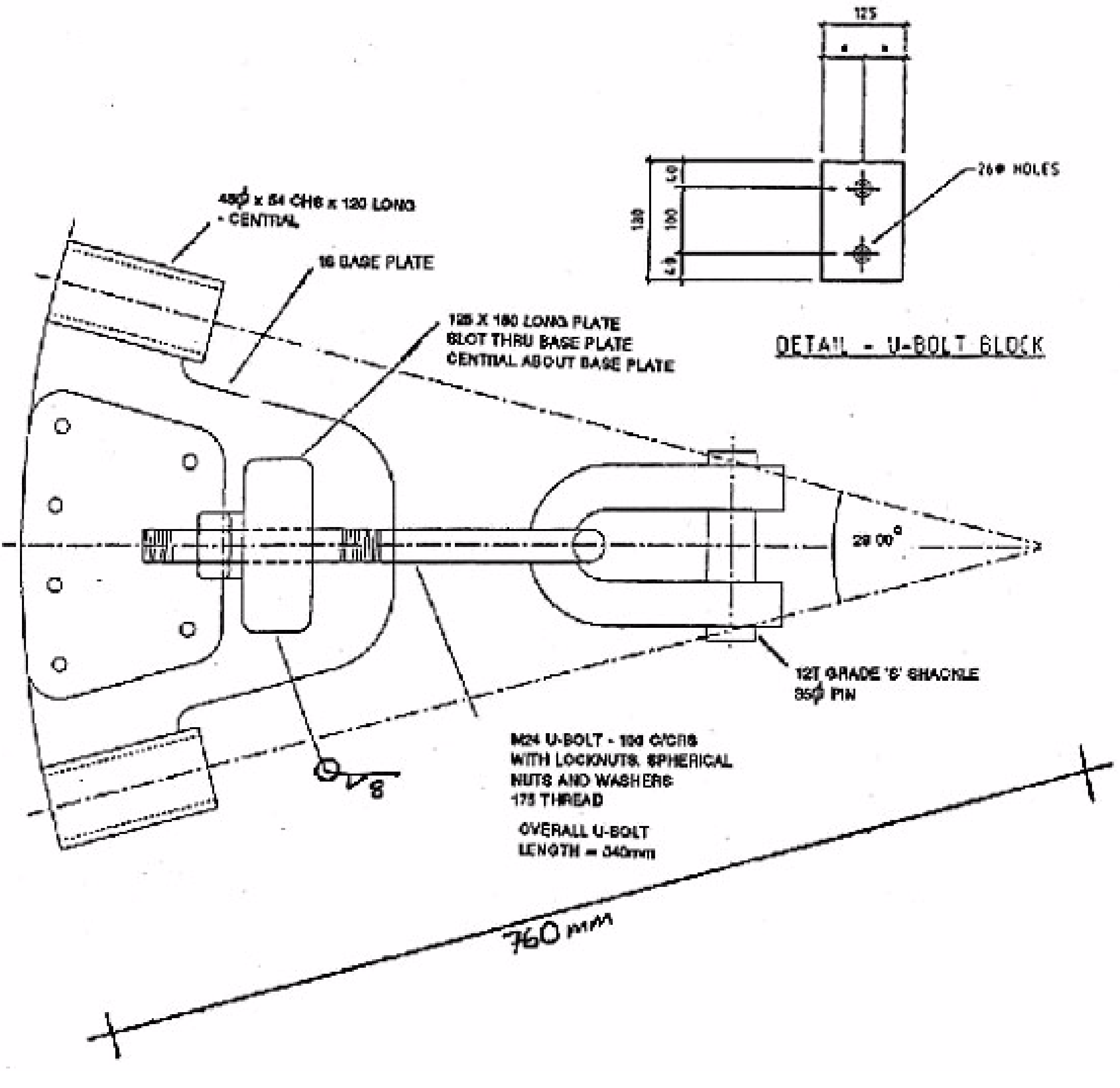
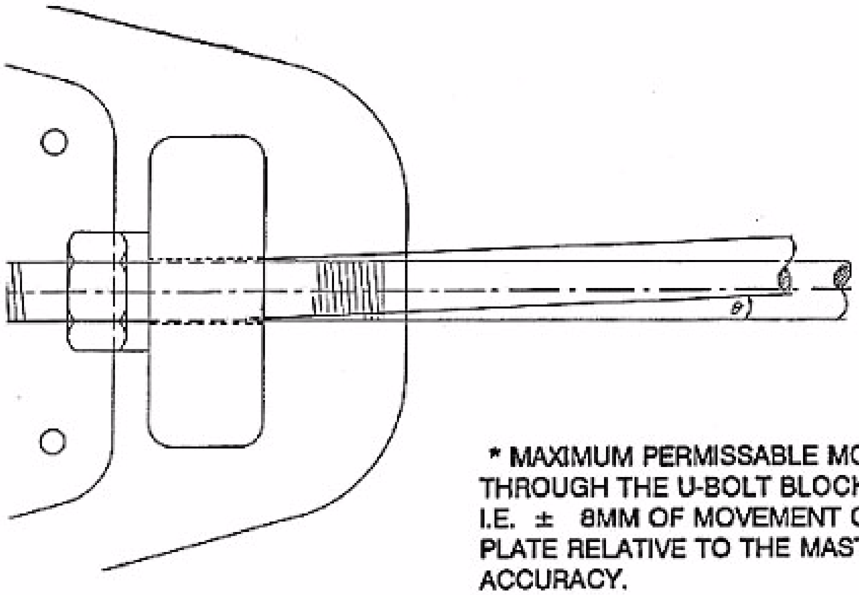


FIGURE C



* MAXIMUM PERMISSABLE MOVEMENT OF U-BOLT THROUGH THE U-BOLT BLOCK θ = ± 2.29°
I.E. ± 8MM OF MOVEMENT OF THE MEMBRANE PLATE RELATIVE TO THE MAST IF SET UP TO 100% ACCURACY.

FIGURE D

3. INSTALLATION PROCEDURE (FOR ONE HYPAR)

3.1 The masts were laid out and aligned to their appropriate base connection plate.

3.2 All mast guy cables were connected to masts, and set to theoretical design lengths.

3.3 The fabric structure was unflaked over the masts and membrane plates were connected to the fabric.

3.4 Catenary cables were run through catenary pockets and set at the membrane plate to the theoretical design length.

3.5 Membrane plates were connected to the mast top cleat, with the U–bolt and shackle. (**Refer Figure C**)

3.6 Mast tops were then lifted by crane,

- Bases of masts pinned
- Masts raked backward
- Long mast guy cables connected to base plates.

3.7 Hollow hydraulic enerpac and temporary cables pull short masts back to connect guys to base plates (Correct fabric prestress achieved)

3.8 Removal of crane.

3.9 Repeat for other Hypars.

NOTE: No inspection was performed during or after installation in terms of the membrane plate to mast alignment, or to the squareness of the membrane plate U–bolt block to the U–Bolt. (Refer figure H)

4. U–BOLT FAILURE SEQUENCE OF EVENTS

4.1 VISUAL INSPECTION

A brief visual inspection from ground was performed 222 Days from installation completion. The wind velocity was approximately 28 knots gusting 35 side on to the Hypars.

There appeared to be very slight vertical movement at the centre of the Hypar, approximately 20 – 30mm

- – no shimmer
- – no waves
- – no visible movement of membrane plates
- All bracing cables appeared to be very firm with all lock nuts still in place.

4.2 *DISCOVERY OF FAILURE*

- 235 days after installation completion a pedestrian heard the sound of a falling object hitting the ground (not far away!)
- The citizen reported this to the Principal Contractor.
- The Square surrounding the Hypars was immediately closed off.
- Temporary restraints were placed around the failed bolt.
- The bottom leg of the U–Bolt had failed.

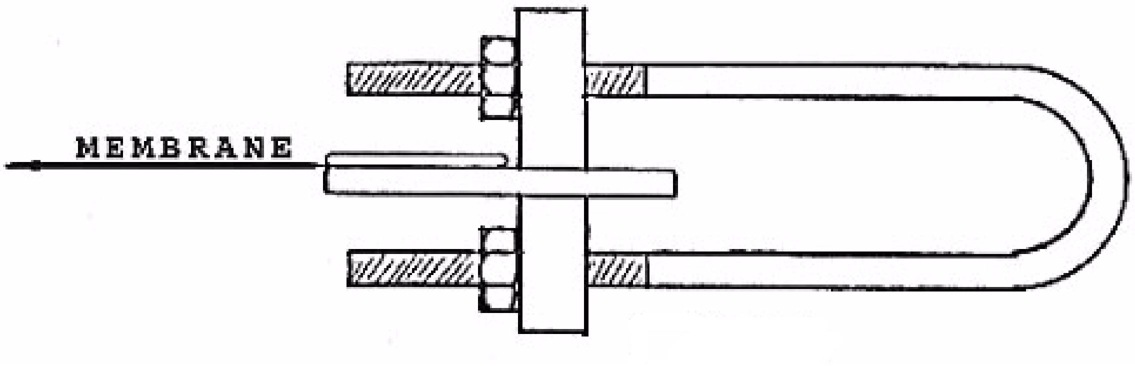


Figure E

4.3 *WEATHER CONDITIONS*

Conditions at Failure

13th April Southerly 10 – 15 knots with rain and drizzle all day

14th April Northerly 20 knots rising to 25 gusting 45 knots by evening. Showers

(Day of failure) 15th April Northerly 15 knots, rising to 25 knots, gusting 45 knots by afternoon. Fine with showers by evening.

16th April Northerly 15 knots, fine weather.

12 such weather patterns had occurred since installation.

*(Canopy is designed to withstand 82 knots 41m/sec)

4.4 *POST FAILURE SITE INSPECTION*

4.4.1 Inspection of Failure Area

- (Failed U–Bolt indicated on Figure A)
- The primary cause of failure was quite clear.

- There was substantial mis–alignment of the membrane plate with the mast top connection point. i.e The U–Bolt was resting and bending on the edges of the U–Bolt Block. This was clearly a result from the initial set up of the structure.

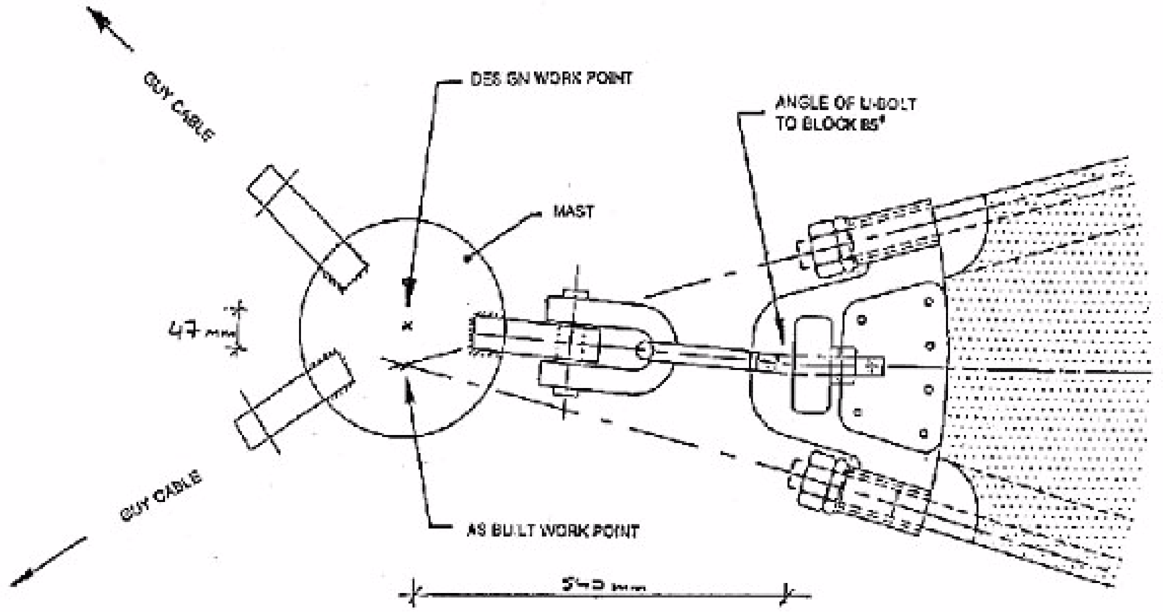


FIGURE F

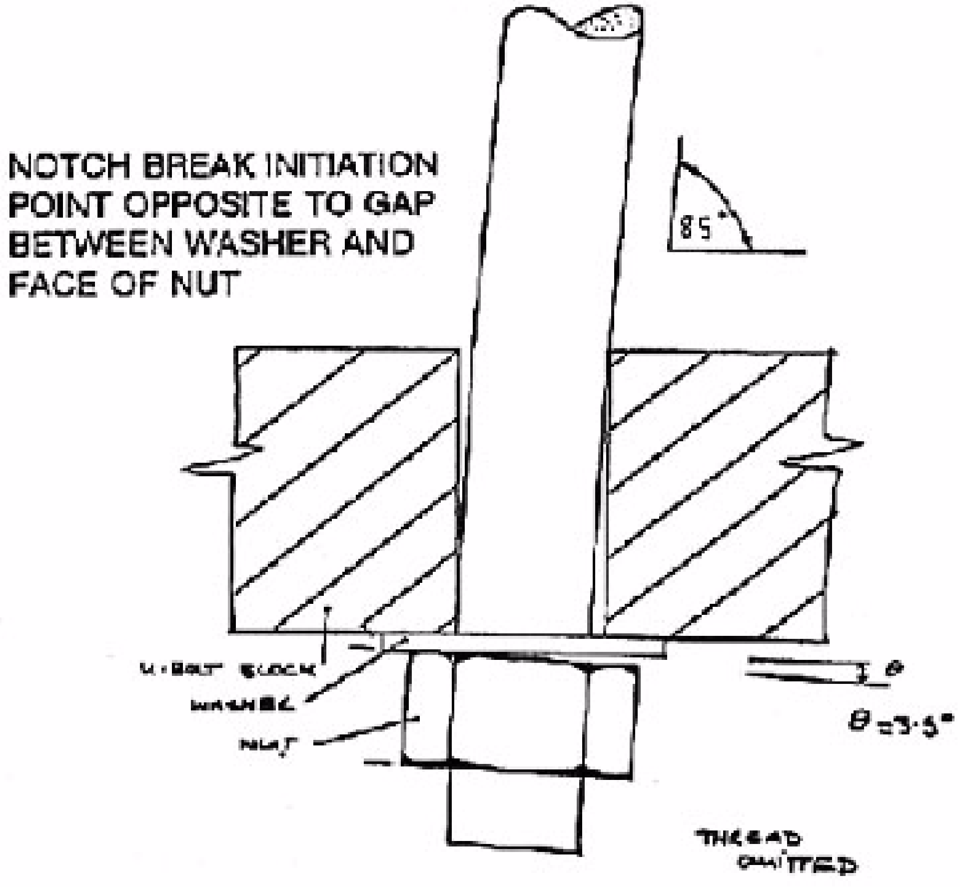


FIGURE G

After observing the failed U–Bolt and the other eleven it was clear that all had been mis–aligned. <u>The failed U–Bolt more so</u>. * Note – short mast membrane plates were out by ≈ 1° as the single guy cable allowed the mast to rotate into a more appropriate position. As opposed to the double guys of the long masts which would not allow any movement.

In all cases the spherical nuts washers were not used. Refer figure C.

The broken bottom leg was due to the length of the U–Bolt not being adjusted evenly. Through the block i.e. more load on the bottom leg than top, hence greater fatigue on the bottom leg.

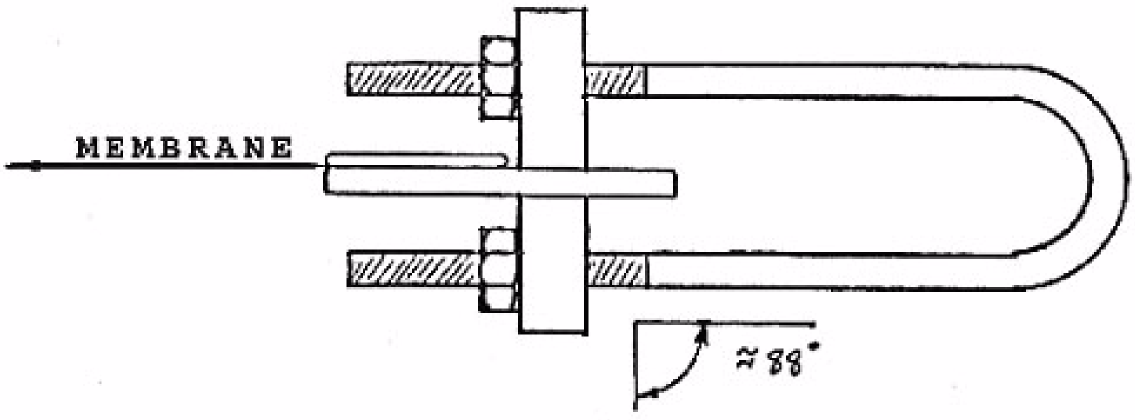


FIGURE H

The break was clearly a metal fatigue situation with a notch initiation at the thread root immediately below the nuts on the first thread turn at the bearing face of the U–Bolt Block.

* Arrow indicates notch initiation

FIGURE I

* The failed U–Bolt was removed for analysis, to ensure materials and method were in accordance with specification and manufacture practice.

5. ANALYSIS OF U–BOLT

(Excerpts from Metallurgist Report)

5.1 VISUAL EXAMINATION

The U–Bolt was manufactured from 24mm bar stock provided by Fletcher Steel in July 1995. A Test Certificated from Aichi Steel Works to SCH440H grade on heat No. 06387 was made available. This indicated that the steel supplied was AICHI Grade 4140 low alloy steel with hardness levels of HB293 to 302 (Brinell) as supplied.

All of the above information indicates that the steel was the correct selection and in the correct condition to meet ISO Recommendation R898 Grade 8.8 category as shown on the drawing. Refer figure C

Grade 8.8 bolts are required to meet minimum of 660 MPa yield stress, 830 Mpa tensile stress and fall between 24 Rc and 34 Rc hardness in the as–supplied condition. **This steel should meet all of the above requirements**.

This U–Bolt has been galvanised prior to use.

The bolt had fractured some 50–60mm from the and of the threads and immediately below the nut on the first thread turn (not available for examination).

The fracture face was revealing on several counts:

- The crack initiation site was multi–positioned, at the root radius of the threads.
- This initiation site exhibited some seven ”ratchet” marks approximately 40% of the total thread circumference.
- The fracture mechanics involved were fatigue–initiated with a multitude of fatigue striations across 60–70% of the surface area.
- The fatigue failure was of a unilateral bending type with indications of a low stress/high cyclic nature.
- The ”critical area” left opposite to the crack initiation was about 20% of the total cross–sectional area. This corresponds to the critical stress involved in the final catastrophic failure under ductile conditions.
- The features of this failure were a good example of variable stress concentrations developed under bending loads on an area of high tensile stress created during high torque settings.

5.2 HARDNESS TESTS

The bolt was ground and tested using Rockwell test methods.

Hardness was found to be 32 – 33 Rc which confirms the hardness quoted by the Dainetsu Corp Certificate.

This means that the U–bolt should exceed the stated minimum 830 Mpa tensile strength requirements easily and achieve something in the order of 1000 – 1050 Mpa on testing.

5.3 THEORETICAL DISCUSSION

Fatigue failure is a difficult subject to explain as most researchers find that being able to predict fatigue is plagued with ”in–situ” situations that cannot be truly replicated in a laboratory situation, and with massive spread of results in any event. However, some significant areas of knowledge have been developed over the years which need attention, if you are to avoid or explain the incidence of fatigue.

Briefly, these can be said to be:

- For fatigue to develop you must have simultaneous action of cyclic stress (wind in this case), tensile stress (included by torque loading of the nut) and **plastic strain** (this **can** happen at very low levels below the true elastic limit).
- The fatigue limits of steels below 400 HB (such as in this case) are generally considered to be 50% of the ultimate tensile strength.
- Ductility is important to fatigue life only under **low cycle** fatigue conditions. This is not considered to exist in this failure.
- Cause No. 1
- Surface conditions are extremely important to onset of fatigue. This includes roughness, scratches, notches, fretting etc. **In this case, cut threads with no radius can reduce fatigue resistance by as much as 70 – 80% as compared to a highly polished surface.**
- Cause No. 2
- Hydrogen embrittlement as a result of poor cleaning practice (often pickling in acid) can introduce high levels diffusion of hydrogen into the steel during galvanising. This will initiate the cracking as the starter mechanism of fatigue. (not found in this case)
- Cause No. 3
- Decarburization of the skin of the steel, such as can be achieved by the use of air atmosphere heat treatment furnaces prior to quench will reduce skin strength and reduce fatigue resistance.
- Cause No. 4
- Internal Defects, such as encountered in ”dirty” steels where slag practice is poor or de–oxidation is out of control, will produce non–metallic defects which act as stress–raisers and initiate fatigue.

6. SUMMARY OF U–BOLT FATIGUE AND FAILURE

After analysing the bolt and studying the site we concluded:

6.1 Primarily the U–Bolt was working in ”bending” caused by mis–alignment due to oversight at installation (Refer Figure F)

Design Rotation = ± 2.29°

Installation Rotation Set up = ± 5.0°

6.2 (Case Study II – Brief)

As found with case study II a similar fatigue failure of a U–Bolt occurred, not caused by mis–alignment, but excessive fabric movement occurred under wind load due to fabric prestress not being achieved at installation. However the failure mechanisms were the same, except the notch break was at the front of the U–Bolt block this time.

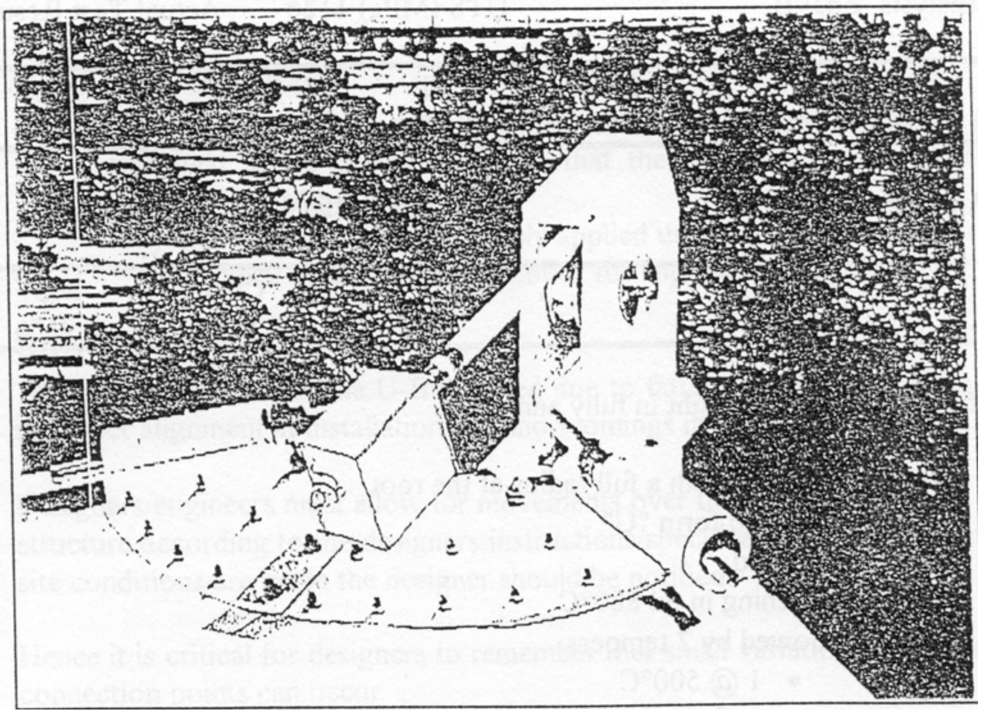


FIGURE J

6.3 Cutting off threads with very little radius at the root increase the chances of notching and hence the overall fatigue resistance is reduced. This increases the chances of crack initiation if bending occurs.

6.4 The concave washer and convex nut were not used. However, as both were galvanised, gauling would occur at relatively low loading and rotation consequently would not occur.

6.5 Insufficient clearance of U–Bolt through U–Bolt block

7. REMEDIAL ACTION

We concluded that the best remedial action was to:

- Manufacture new U–Bolts from higher fatigue resistant material
- Re–align masts
- Oversize U–Bolt block holes
- Re specify concave/convex seating washers

7.1 NEW U–BOLT SPECIFICATION

New U–Bolts were manufactured. New Material = En39B.

A higher tensile steel with higher fatigue resistance

Typical Analysis En39B UTS (MPa) 1126 Actual Test Result

C	Mn	Si	Ni	Cr	Mo
0.15%	0.5%	0.2%	4.2%	0.85%	0.2%

Typical Analysis AISI 4140 UTS (MPa) 850 – 1000

C	Mn			Cr	Mo
0.40%	0.8%			0.95%	0.25%

The material was brought in fully annealed.

- Threads were cut with a full radius at the root
- Bars were bent to form ”U”.
- Then heat treated
    - Quenching in oil 880°C
    - Followed by 2 tempers
        - 1 @ 500°C
        - 1 @ 530°C

    Giving a final hardness of 34.5 HRc

After heat treatment the bolts were shot blasted to further improve fatigue resistance, in particular the material at the threads.

Shot blasting removes any skin imperfection i.e. scratches, notches and also polishes the outer skin.

Prior to galvanising, mechanical cleaning i.e. (shot blasting) minimises pickling time (cleaning process) to 2 minutes. This helps to minimises the chance of hydrogen embrittlement occurring.

7.2 SEATING WASHERS

Concave seating washer with convex high load plastic inserts were used to allow the U–Bolts to pivot into correct alignment during re–tensioning of the structure. This would also allow for displacement under wind loads and return the U–Bolt to original central position, providing all variables remain unchanged overtime.

i.e – Fabric prestress
– Cable lengths
– Connection points

7.3. U–BOLT BLOCKS

The 26mmϕ hole through the blocks were drilled out to 30mmϕ to allow freer movement of U–Bolt without contacting the edges of the block

(Drilled in–situ)

7.4 MAST RE–ALIGNMENT

– As the new U–Bolt were replaced the masts were aligned so that they remained in the design plane, so that the U–Bolt in static condition was centralised through the block.

– Guy cable tension was then evenly applied until final prestress was reached.

– * Final check of all connection points for alignment

8.0 CONCLUSION

There is not doubt that the U–Bolt failed due to fatigue mechanisms, resulting from incorrect alignment at installation and shortcomings in membrane plate design.

Designers/engineers must allow for movements over time. Installers must set up the structure according to the designers instructions/specifications. If alterations due to site conditions are made the designer should be notified.

Hence it is critical for designers to remember that small variations in the positions of connection points can occur

(a) prior to installation

(b) after installation

These variations should be taken into account.

(1) Variations prior to installation could be alterations in site conditions, tolerances slightly bigger than allowed for in the design (sometimes in opposite directions) etc.

(2) Variations after installation, could be slight misalignment caused by (a) but magnified and transferred to other points, movement under loading, and changing conditions (different wind directions), initial stretch, fabric tension relaxations, thermal effects on long cable lengths etc.

The designers/engineers need to consider the following variations as mentioned above and including:

- Construction tolerances
- Installation tolerances
- Fabric tension relaxation
- Connection point movements
- Movement of metals on metals (including protective coatings)
- Metal fatigue
- Connection component specification

Installers and designers must always create a best chance/worst case scenario, as we can never eliminate all contributing effects of fatigue developers.

References:

Understanding How Components Fail, Donald J. Wulpi

Fletcher Steel: Engineering Steels, January 1994

Acknowledgements:

South Auckland Forgings