The Welding Institute

The Welding Institute (North Scottish Branch) and Institute of Corrosion (Aberdeen Branch) present

High Tensile Steel Bolts and Nuts – Hydrogen Embrittlement and Failure in Corrosive Environments

JOINING PROFESSIONAL INTEGRITY AND RECOGNITION

INSTITUTE OF CORROSION

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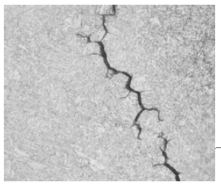
The Welding Institute

Joint meeting
23rd September 2020

INSTITUTE OF CORROSION



High tensile steel bolts and nuts – hydrogen embrittlement, and failure in corrosive environments

Alan Denney

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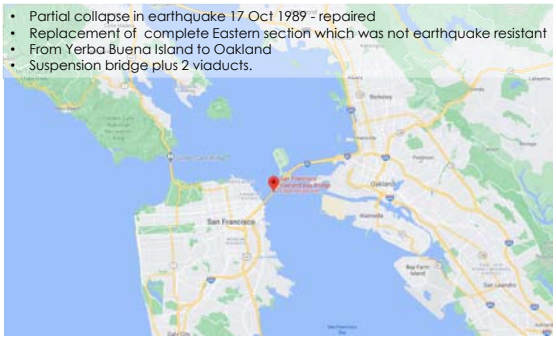
San Francisco-Oakland Bay Bridge – Eastern span replacement

- Partial collapse in earthquake 17 Oct 1989 - repaired
- Replacement of complete Eastern section which was not earthquake resistant
- From Yerba Buena Island to Oakland
- Suspension bridge plus 2 viaducts.



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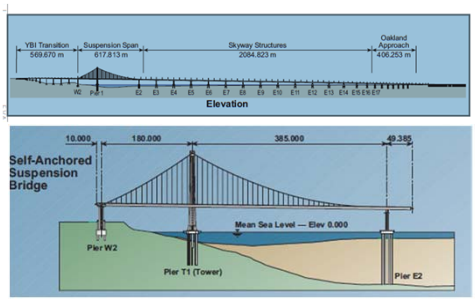
San Francisco-Oakland Bay Bridge - replacement



http://baybridgeinfo.org/sites/default/files/pdf/SFOBB-SAS%20Evaluation%20of%20the%20A354BD%20Rods%20Final%20Report.pdf

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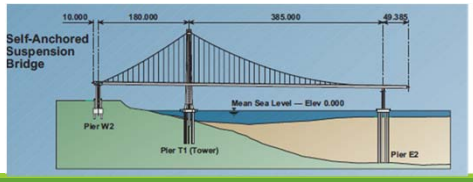
San Francisco-Oakland Bay Bridge – suspension bridge

96 No 3 inch diameter rods anchor the superstructure to the support piers

- galvanized ASTM A 354 grade BD anchor rods – pre-installed 2008

Superstructure erected. In March 2013 rods were pre-tensioned hydraulically to 70% of UTS

32 of the 96 anchor rods fractured within two weeks



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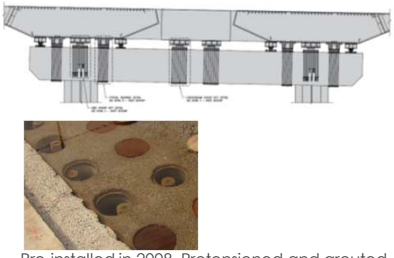
San Francisco-Oakland Bay Bridge



Pre-installed in 2008. Pretensioned and grouted 2013

Cause of failures: hydrogen embrittlement from corrosion – stress corrosion cracking

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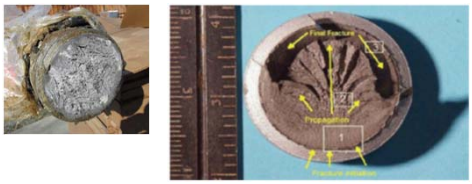
San Francisco-Oakland Bay Bridge - investigations



In testing they managed to replicate the differences in failure behaviour between sets of rods.

There was a correlation of failure with low toughness material.

The rods which failed were 'tensioned above their 'hydrogen embrittlement threshold'.

There was 'a failure of the corrosion protection measures'.

Remedial works cost $25m

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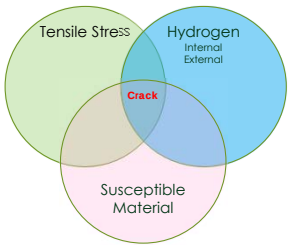
The three conditions for hydrogen embrittlement



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Hydrogen embrittlement of fasteners – an old problem

Known problem with electroplated and galvanized high tensile bolts with UTS over 1000 N/mm^2:

Emley Moor tv transmission tower 1970

V grade bolts (UTS 1000-1150 N/mm^2)

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Hydrogen embrittlement in fasteners – basics 1

- Material: hydrogen embrittlement risk with steel if UTS >1000 N/mm^2
- Hydrogen sources – internal:
  - hydrogen from steelmaking
  - pickling prior to galvanizing or electroplating
  - Electroplating process
- Hydrogen source – external: corrosion
  - Hydrogen generation by cathodic reaction
  - Hydrogen migration
  - Crack formation and propagation
- Stress
  - Loading of the fastener
  - Stress raisers

Stress corrosion cracking – a form of environmental cracking

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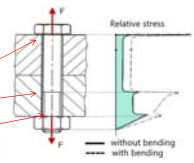
Hydrogen embrittlement in fasteners –basics 2

The clue to whether it is internal hydrogen embrittlement or due to the environment is the time to failure

- Internal – hours to day
- Environmental – time dependent – weeks to years

- When bolts are stressed atomic hydrogen migrates to the location of greatest stress,
  - at the transition under the head.
  - at the transition from thread to shank.
  - in the first engaged thread.
- Failure occurs at a stress less than the UTS of the fastener
- Failure is sudden and dramatic



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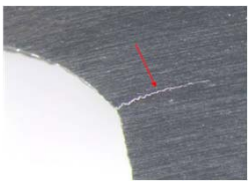
Possible issue due to internal hydrogen

Photograph redacted



Large diameter galvanized bolt which failed shortly after installation

No signs of corrosion

Section under the head through a comparable bolt with no failure

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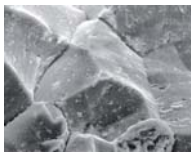
Failure due to charging during electroplating



Embrittled from zinc electroplating.

Atomic hydrogen diffuses to the grain boundaries, resulting in intergranular failure.

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Preloaded structural bolts – the bolt assembly

Preloaded bolts to EN 14399 (high strength friction grip bolts)

High tension loads in bolts - up to 70% of UTS

Load taken in shear – slip factor depends on surface condition

Mechanical properties - bolts to EN 898-1 nuts to EN 898-2

The standards state requirements only up to a shank diameter of 39mm.

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Preloaded structural bolts - Design

- Eurocode 3 - EN 1993 design of steel structures
  - Design of joints – bolted connections under EN 1993-1-8.
- Covers requirements for the bolt systems made to EN 14399.
  - System HR to part 3 (High resistance)
  - System HV to part 4 (High strength)

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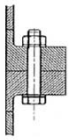
Use of large diameter bolts in wind turbine structures



Internal flange connection between monopile (MP) and transition piece (TP)

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Use of large diameter bolts in wind turbine structures

M64 bolt, property class 10.9 bolt

Connection of the rotor hub to the turbine and the blades to the rotor hub

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Bolt and nut property classes in EN 898-1 and 898-2

Property classes of bolts: 8.8, 10.9 or 12.9
First figure – represents nominal tensile strength.
10 = 1000 N/mm^2
Second figure – represents lower yield strength.
9 = 90% of tensile strength. 1000 x 90% = 900 N/mm^2

Item	Property class	Yield/ 0.2% P.S. N/mm^2 min.	UTS min	Charpy V minus 20 °C	Core Hv_{10} max.	Surface Hv_{10} max.
Bolt	8.8	640	830	27J	335	-
Bolt	10.9	900	1040	27J	380	380
Bolt	12.9	1100	1200	27J	435	435

Property class of nuts: 8, 10 or 12
Represents nominal tensile strength but only hardness is tested.

Item	Property class	Thread Hv_{10} max.	Surface Hv_{10} max.
Nut	8	353	353
Nut	10	353	353
Nut	12	353	353

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Conventional wisdom

- Fasteners to property class 8.8 (UTS 830 N/mm^2) are not considered susceptible to hydrogen embrittlement
- Fasteners to property class 10.9 (UTS 1040 N/mm^2) are stated as not susceptible to hydrogen embrittlement provided the hardness is below 380 Hv.

But failures occur in fasteners of significantly lower hardness than 380 Hv

Warning in EN 14399-4:2015

Fasteners to property class 12.9 (UTS 1200 N/mm^2) are considered susceptible to hydrogen embrittlement due to their hardness exceeding 380 Hv.

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GL and DNV-GL guidelines re: SCC risk

DNV GL standard 0126

The maximum bolt property class is 10.9 (except for below waterline).

Below 'Highest astronomical tide' the maximum bolt property class is 8.8

DNVGL-ST-0126. Support structures for wind turbines. Edition July 2018. DNV GL AS

4.2.6.1 The bolt property class for steel structures and interfaces between tower and concrete foundation part shall be designed with the equivalent maximum bolt property class of 10.9, see ISO 898-1 in order to avoid the risk of hydrogen embrittlement.

4.2.6.2 The bolt property class for offshore steel structures below HAT shall be designed with the equivalent maximum bolt property class 8.8, see ISO 898-1.

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Failures seen by AKD

Fasteners with poor metallurgical features can suffer SCC even if supplied to lower hardness than 380 Hv

Example 1

Galvanized nuts with typical hardnesses of 300 – 350 Hv5 failed by SCC.

Example 2

Failures in galvanized fasteners under the head. 337 – 339 HB (equivalent to 341 – 344 Hv).

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Example 1 – nut failure

Property class 10 nuts. Hardnesses 300 – 350 Hv5 measured in the threads. Failed by SCC.

Photographs redacted

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Example 2 – failure at the bolt head/shank transition

Fracture found approximately 9 months after final torqueing of bolt

Evidence of corrosion formation

Photographs redacted

Drying stains down the shank of the bolt

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Example 2

Photographs redacted

Manufacturers QC hardness results:

Core hardness 337 HB

'Fringe area hardness' 339 HB

Surface hardness measured with Hv 0.3: max 339

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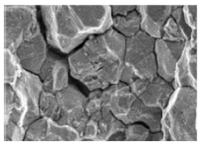
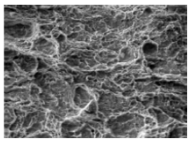
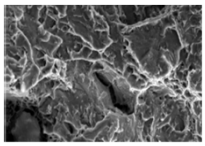
Crack morphology

HE cracks are intergranular



Crack progression - mixed mode





Final fracture is ductile

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The requirements for large diameter bolt sets

DASt021 states requirements for bolt sets for diameters exceeding 39mm

- *dimensional* requirements for HV bolting assemblies to M72
- thread requirements (by reference to other standards)
- States preloading torque requirements
- States QC requirements
- Requires a compliance certificate

Specific requirements:

- Hardness test requirements: limiting hardness 353 Hv30
- Requires nuts to be 'lubricated under process conditions'.
- DSV requirement on galvanizing are to be met

DAST 021 for hot-dip galvanized bolt EN 14399-4:2015, High-strength structural bolting assemblies for preloading. System HV. Hexagon bolt and nut assemblies. Deutscher Ausslu ß für Stahlbau. (German committee for steel construction).

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Steel composition and properties

Composition requirements from the EN specifications leave wide scope for use of different alloying systems/compositions

Item	Property Class	Material and heat treatment	C min.	C max	Mn min.	P max.	S max.	B max
Nut	8	Carbon steel, QT	-	0.58	0.30	0.048	0.058	-
Bolt	8.8	Carbon steel with additives (e.g. B Mn or Cr)	0.15	0.40	0.60	0.035	0.035	0.003
		Carbon steel QT	0.25	0.55	-	0.035	0.035	-
Nut	10	Carbon steel, QT	-	0.58	0.30	0.048	0.058	
Bolt	10.9	Carbon steel, QT	0.25	0.55	0.70	0.035	0.035	0.003
		Carbon steel, QT, with additives (e.g. B Mn or Cr)	0.15	0.35	0.70	0.035	0.035	0.003
		Alloy steel QT (g)	0.15	0.35	0.70	0.035	0.035	0.003
Note g	Shall contain one of: Cr 0.30% min, Ni 0.30% min, Mo 0.20% min, V 0.10% min. (with rules for combinations							
Note	Simplified. See the standards for the permitted variations to the above							

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Composition – it makes a difference

- Deutscher Shraubenverband (DSV) compared the SCC performance of 27MnB5 and 32CrB4 steels*:
- The 27MnB5 failed in 10 – 30 hours. The 32CrB4 steel did not fail within 72 hours (the test duration)

* Static test in NaCl solution stressed at 0.9 x Fmax.

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DSV recommendations

Composition and steelmaking

- Carbon content – limit it to 0.35% maximum
- Minimise the S and P content (≤ 0.015%)
- Select a steel which will give high toughness by the use of alloying with for example, B, Cr, Mo and Ti
- Use steels which, when annealed form 'hydrogen traps' – finely divided carbides: Cr, Mo, W, Ta, Nb, Zr and Ti

Heat treatment

- Avoid the presence of δ ferrite by dephosphorization prior to h.t.
- Furnace anneal, quench and temper - control the furnace atmosphere
- Limit the strength (≤1170 N/mm^2) and surface hardness (≤ 375 Hv 0.3) by control of heat treatment
- Ensure careful control of tempering to avoid temper embrittlement

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Coatings for bolts and nut

- Galvanized zinc
- Zinc flake
- Electroplated zinc
- Electroplated zinc/nickel
- (Sherardised)

Potential risks of hydrogen embrittlement due to pickling or plating process.

DNV-GL-ST-0126 states

4.2.6.5 Bolt threads may be rolled before or after heat treatment, followed by a thermal coating process. This thermal coating process may be e.g. hot-dip galvanizing. Electrolytically galvanized corrosion protection is not allowed.

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Difference in SCC threshold between coating systems

DSV investigated the load threshold for SCC for:

- Galvanized zinc
- Zinc flake coating
- Electroplated Zinc
- Electroplated Zinc/nickel

Findings

- Galvanized zinc and electroplated zinc - had a lower threshold that an uncoated bolt
- Electroplated Zn/Ni coating and the zinc flake coating – had a higher threshold than an uncoated bolt

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DSV requirements* on galvanizing

- Use approved inhibitors in pickling bath
- Pickling time limited to 15 minutes at room temperature
- Galvanizing temperature to be 445 - 470 deg C
- Conduct WSR tension test to check for hydrogen embrittlement

Possibly better to blast clean rather than clean by pickling

* Directive for the manufacture of hot-galvanized bolts and DIN EN 14399-1/4. Deutscher Schraubenverband e.V. Gemeinshchaftsausschuss Verzinken e.V.

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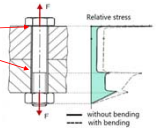
Other DSV recommendations*

Design of bolt assemblies

- Control transition radius
- Control form of thread run-out at transition
- Set limits on surface defects – thread roll overs (EN 26157-3)
- Select coating type considering hydrogen relationship
- Control installation conditions - avoid bending loads



* Dr-Ing S. Beyer, Dr- Ing M. Duchadt, C. Krauß, Dr-Ing R. Langrebed.
Hydrogen-induced stress corrosion cracking in high-strength bolts of large dimensions.
Cause – Influences – Remedial action
VDI Annual Convention. Deutscher Schraubenverband E.V. Oct 2013 (German Bolt Association)

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Not just an issue in a marine environment

November 2014 two bolts fell. 5 fell in all (to June 2015).

'Precautionery tethering' installed

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Only temporary – but a situation to be avoided

Photograph redacted

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Conclusions

Controls can be put in place to reduce the risk of hydrogen embrittlement and stress corrosion cracking:

- the bolt materials,
- their heat treatment and metallurgical controls
- coating systems and their application
- quality control and testing requirements

Control of hydrogen embrittlement from manufacture lies in well applied manufacturing controls

There is a risk of stress corrosion cracking with the use of fasteners with a UTS > 1000 N/mm^2 in a corrosive or marine environment.

The guideline of 380 Hv as the threshold for stress corrosion cracking is not conservative.

The main means of avoidance of stress corrosion cracking is to control the environment.

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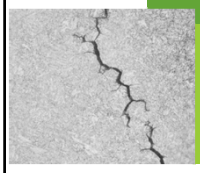
High tensile steel bolts and nuts – embrittlement and failure in corrosive environments



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