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THE MOTT MACDONALD GROUP IS A MULTIDISCIPLINARY CONSULTANCY WITH HEADQUARTERS IN THE UNITED KINGDOM. IT PROVIDES ENGINEERING, MANAGEMENT AND DEVELOPMENT SERVICES INTERNATIONALLY, WITH 16,000 STAFF IN 150 COUNTRIES. MOTT MACDONALD IS ONE OF THE LARGEST EMPLOYEE-OWNED COMPANIES IN THE WORLD.

MOTT MACDONALD WAS ESTABLISHED IN 1989 BY THE MERGER OF MOTT, HAY AND ANDERSON WITH SIR M MACDONALD & PARTNERS. IT HAS WON MORE THAN 500 INDUSTRY AWARDS IN THE LAST FIVE YEARS AND IS AMONG THE TOP RANKED FIRMS IN THE ANNUAL LEAGUE TABLES PUBLISHED BY ENGINEERING NEWS RECORD AND NEW CIVIL ENGINEER. PROJECTS COMPLETED INCLUDE THE HONG KONG INTERNATIONAL AIRPORT, WEMBLEY STADIUM AND THE CHANNEL TUNNEL.

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Paul Lambert Is Head Of Materials And Corrosion Technology For Mott Macdonald, Based In Altrincham Near Manchester, United Kingdom. He Has Over 30 Years' Experience In The Investigation Of Structural Durability And Degradation And In The Development Of Novel Remedial Techniques For Many Types Of Structures.

Paul Is Visiting Professor At The Centre For Infrastructure Management At Sheffield Hallam University Where He Carries Out Research Into Novel Materials, Protective Coatings And Repair Technologies. He Is A Fellow Of The Institute Of Materials, Minerals And Mining, A Fellow And Past President Of The Institute Of Corrosion, A Chartered Materials Engineer, A Chartered Corrosion Scientist And A NACE Certificated Corrosion Specialist.

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AN INTRODUCTION TO CORROSION

MECHANISMS

EXAMPLES

COSTS

Steel

- Availability and relatively low cost
- Strong and tough
- Ability to be formed into the required sections
- Ability to be joined by welding
  - upper limit of around 0.25% carbon

Steel

- Relatively simple alloys of iron and carbon with various other alloying elements, principally manganese
- Manganese is added to:
  - reduce embrittling effects of iron sulphide during secondary steelmaking processes
  - give low-temperature toughness

Steel for Construction

Steel for Reinforced Concrete

- Takes the tensile load of the concrete beams or slabs
- Carries a proportion of the compressive stress
- Withstands tensile stresses that may arise due to eccentric load, as in columns
- Withstands sheer stresses in beams near to supports

Steel for Reinforced Concrete

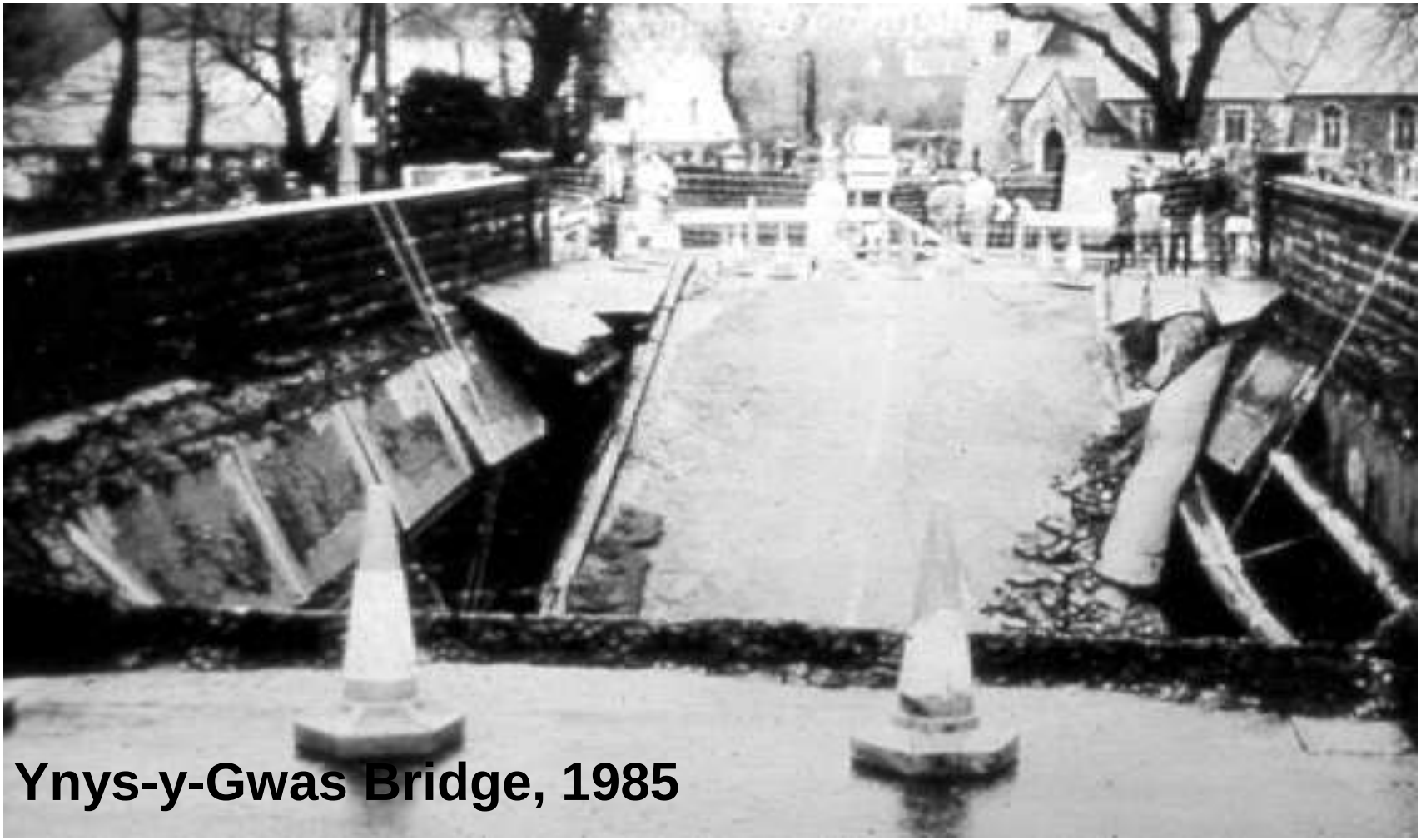
- Prevents propagation of cracks initiated in the concrete
- When used near the surface in mass concrete, reduces cracking by drying shrinkage
- In some cases, is used to prevent spalling of concrete surfaces due to fire

Steel for Reinforced Concrete

- Bond between steel and concrete is important to allow load transfer
- Bond depends upon a number of factors:
  - area of contact
  - strength of concrete
  - condition of the steel surface
    - thin layer of adherent rust improves bond
    - so does use of ribbed bars

Corrosion Awareness Day 2017

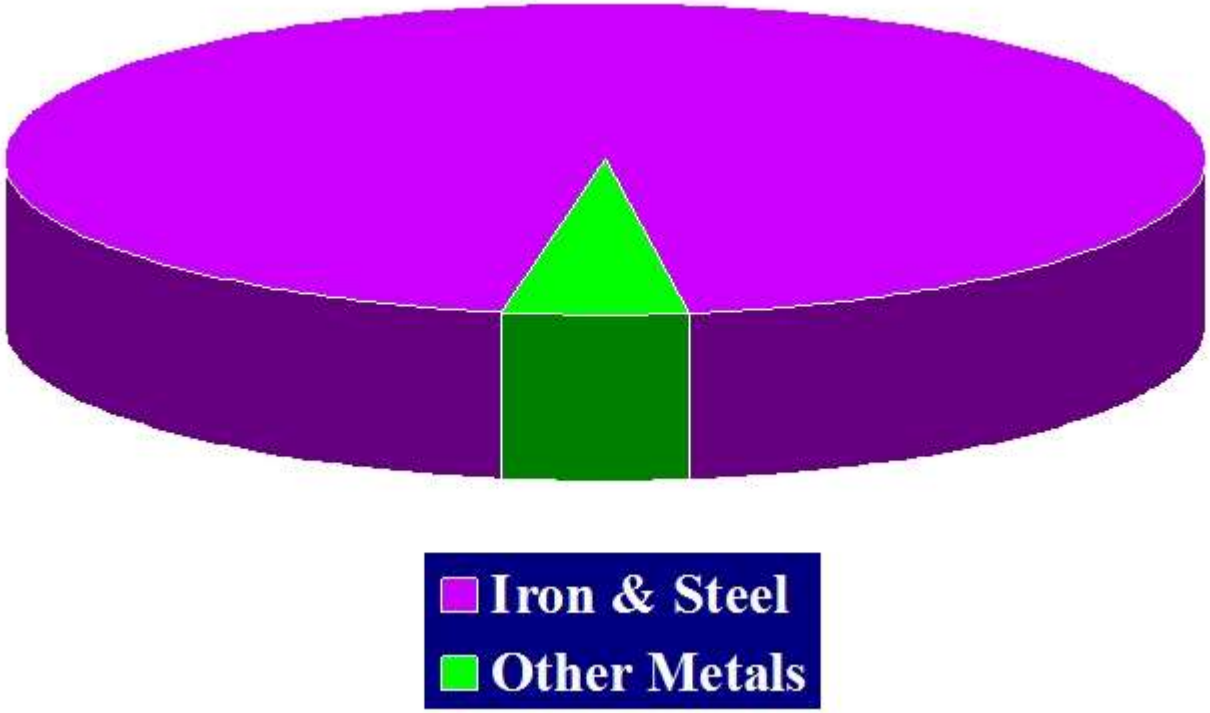
Corrosion Awareness Day 2017


Ynys-y-Gwas Bridge, 1985

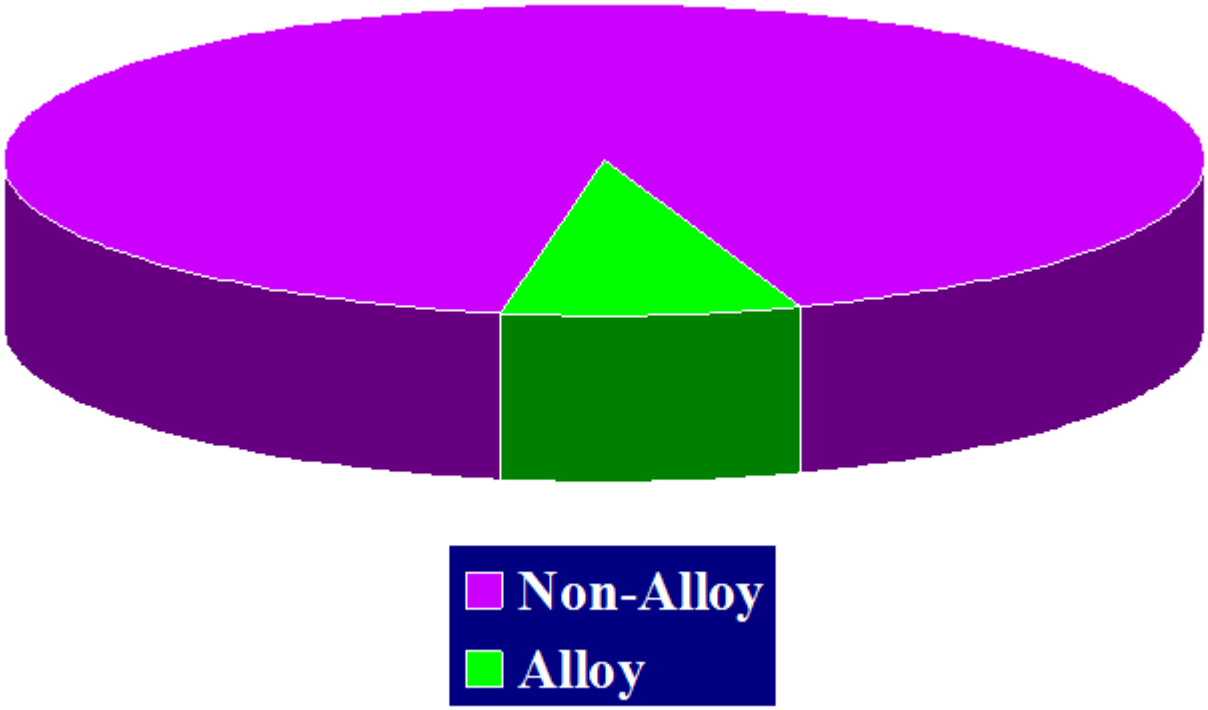
So Why Use Steel?

- Steels are the backbone of the built environment
- A range of relatively simple iron-carbon alloys
- They offer an excellent combination of properties
  - Relatively inexpensive
  - Easily formed and joined
  - Range of mechanical properties
  - Recyclable

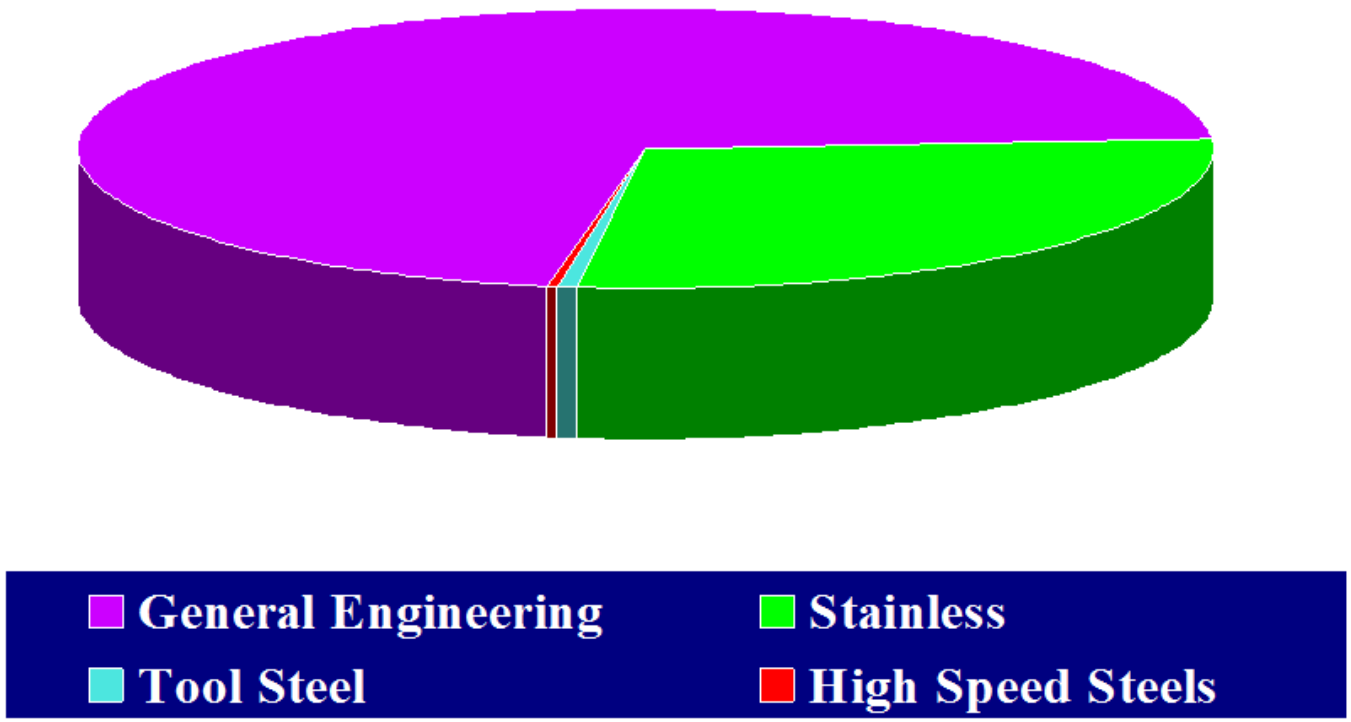
Metals Usage - World Wide

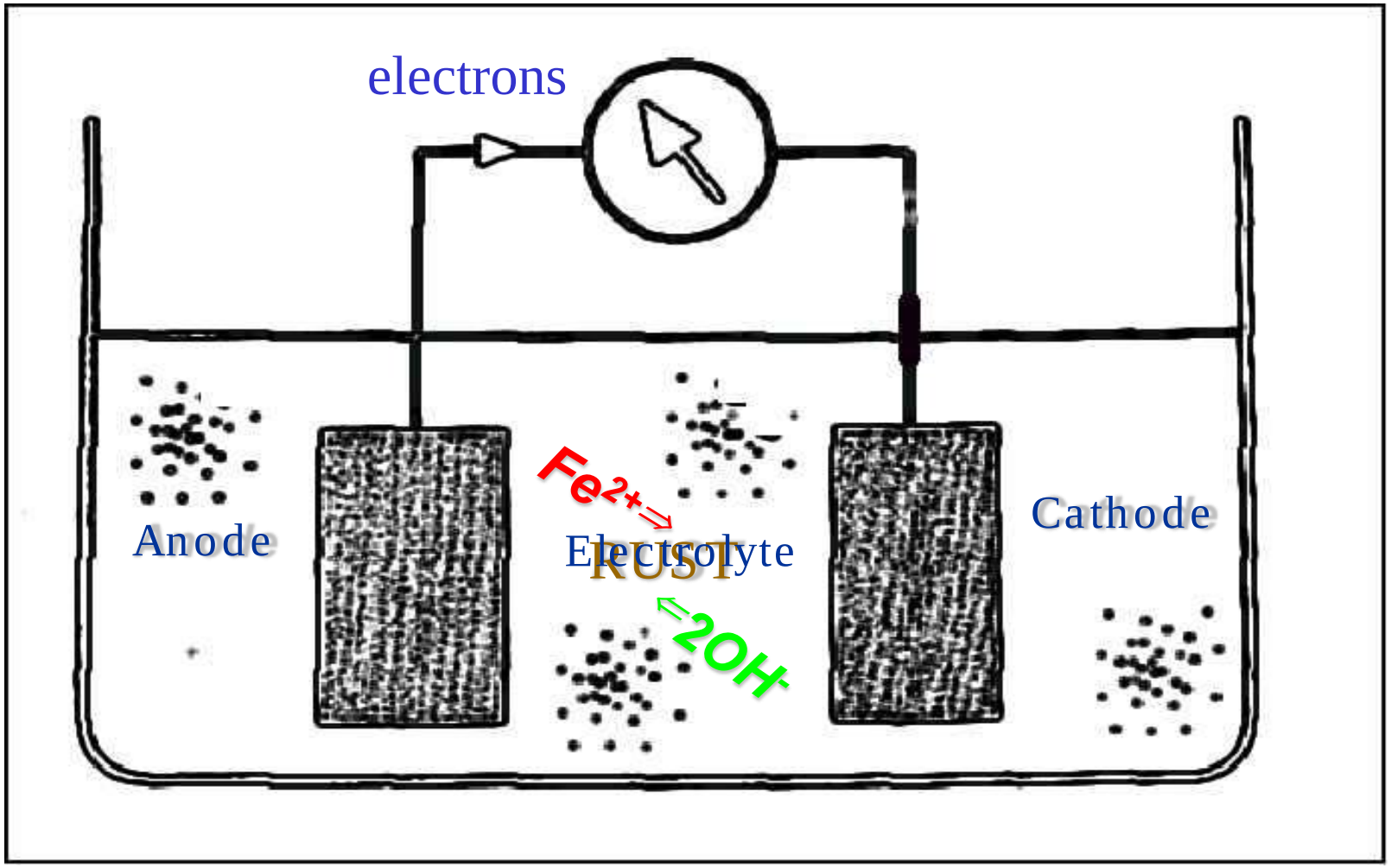


Steel Usage - Alloy & Non Alloy



Alloy Steels




electrons
Anode
Fe2+
Electrolyte
RUST
2OH-
Cathode

Why does steel corrode ? (1)

- Differences in electrical potential on the surface form ANODIC and CATHODIC sites

- At anodic sites the metal oxidises:

  – $Fe\ (metal) \Leftrightarrow Fe^{2+} + 2e^{-}$

Why does steel corrode ? (2)

- Simultaneously, reduction occurs at cathodic sites, typically:
  - $\frac{1}{2}O_2 + H_2O + 2e^-$ (metal) $\Leftrightarrow 2OH^-$ (aq.) or
  - $2H^+$ (aq.) $+ 2e^-$ (metal) $\Leftrightarrow H_2$ (gas)
- Electrons are conducted through metal while ions travel through electrolyte

Anodes & Cathodes

General Corrosion

- Uniform attack of the metal surface
- Low rate of penetration
- Potentially greater degree of contamination
- ‘Typical’ rates are available for most metal/environment combinations
- Difficult to design against
- May require protection - e.g. coatings

General Corrosion

Pitting Corrosion

- Highly localised, high rate corrosion
- Rapid perforation of sections
- Several causes, including chloride ions
- Once initiated, pits can be self perpetuating
- Often associated with stagnant conditions
- Coatings can provide barrier but any defects can become active anodic sites

Pitting Corrosion

Crevice Corrosion

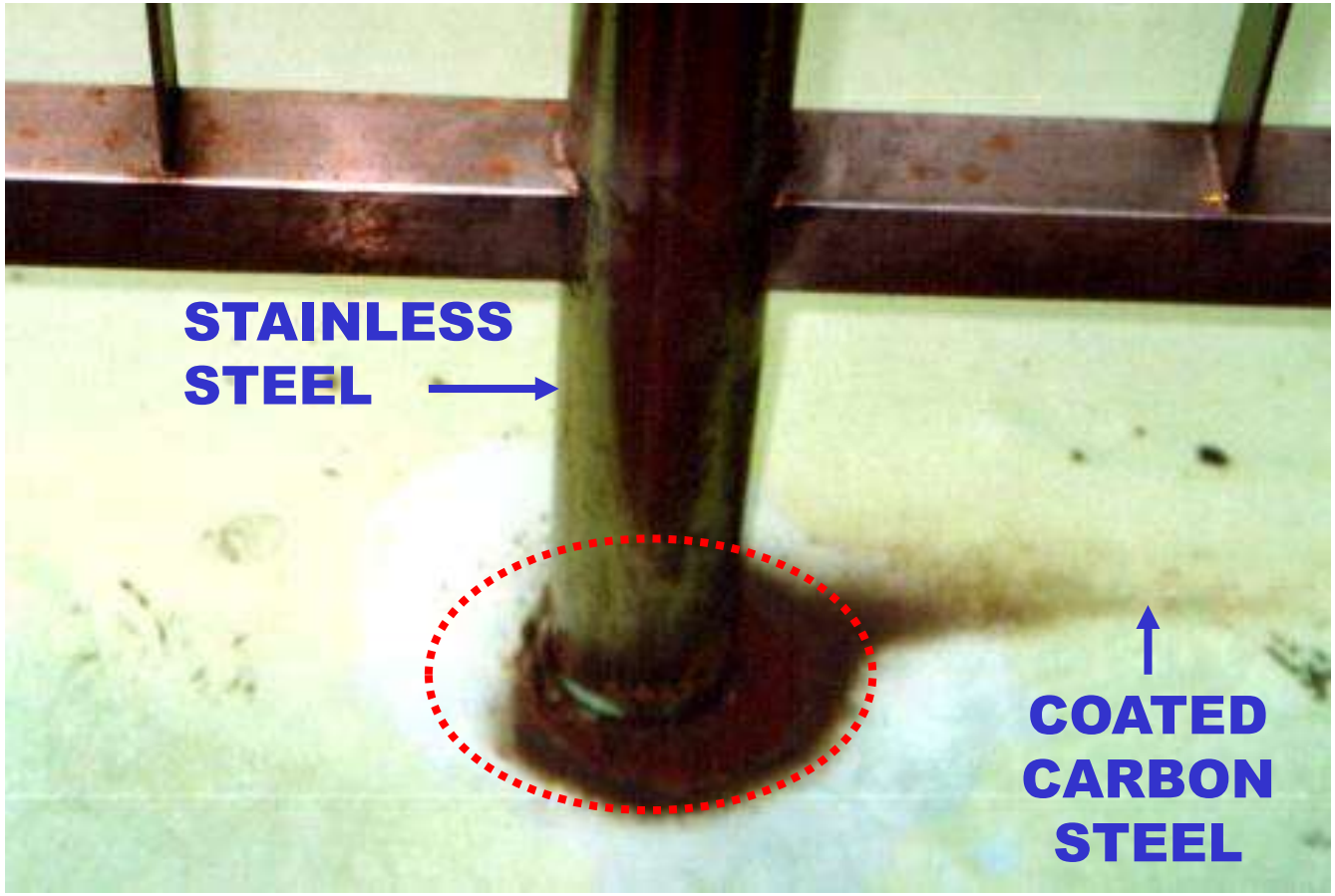
- Typically occurs in gaps between two surfaces
- Only one surface needs to be metal
- Surface deposits can also produce crevices
- Corrosion cell caused by differential oxidation
- The smaller the crevice, the more intense the corrosion
- Must be designed-out or filled-in

Crevice Corrosion

Bimetallic Corrosion

- Five conditions must be satisfied:
  - an environment in which the ‘anode’ can corrode
  - an electrolytic path
  - an electronic path
  - a large potential difference
  - no restriction of the reactions at the ‘cathode’
- Control involves preventing or interfering with one of these requirements

Bimetallic Corrosion



Galvanic Series for Seawater

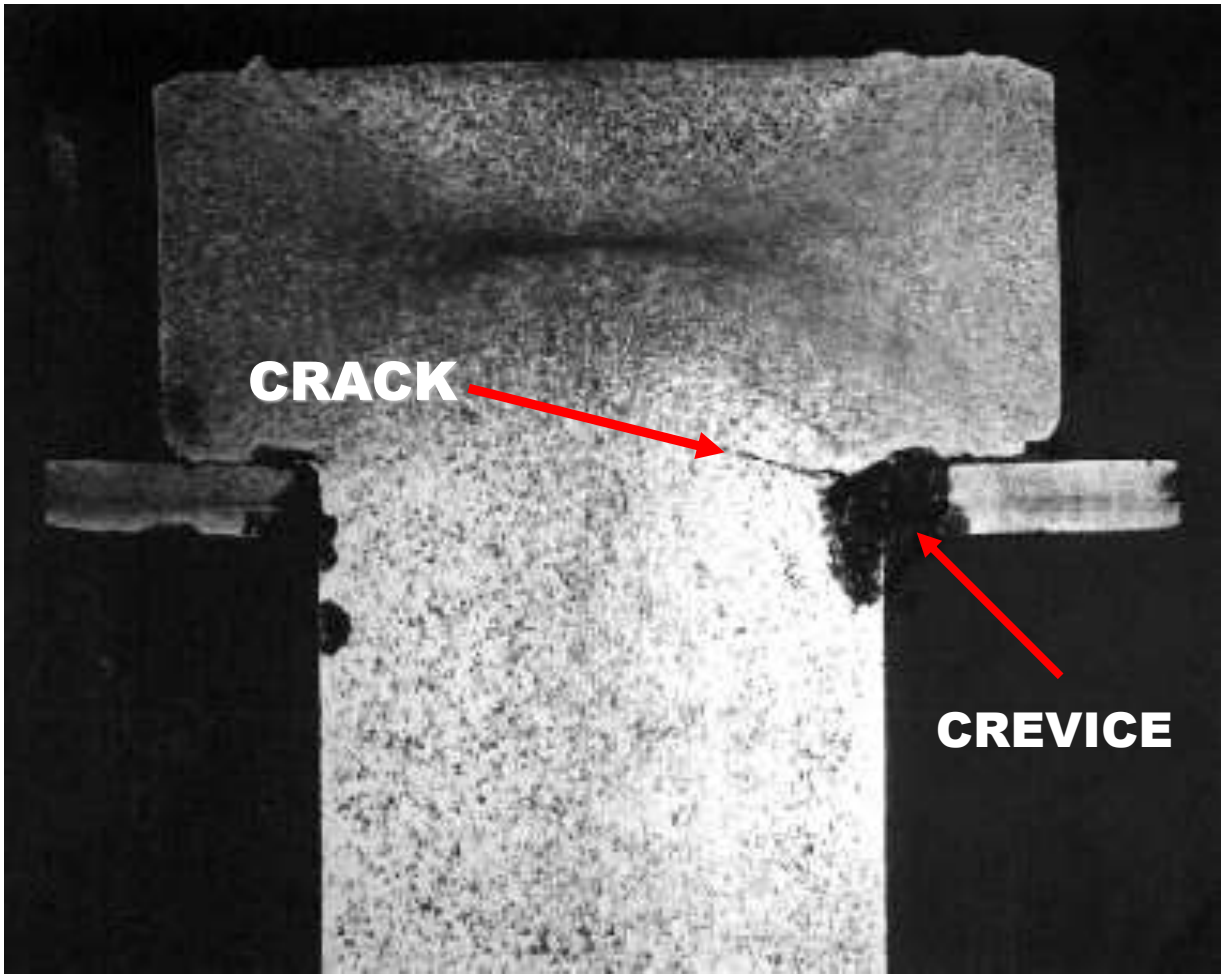
Electro Positive	Graphite	
	Platinum	
	Gold	
	High Alloy Stainless Steels	{Super Austenitic} {Super Duplex}
	Titanium	
	Nickel Chrome Molybdenum Alloys	{625; C-276}
	Low alloy stainless steels (eg 316)	(PASSIVE)
	Alloy 400/Alloy K-500	
	Silver	
	Nickel Aluminium Bronze	
	Copper nickel (70/30; 90/10)	
	Gunmetals/Tin Bronzes	
	Brasses	
	Tin	
	Lead	
	Austenitic Cast Iron	
	Low alloy stainless steels (eg 316)	(ACTIVE)
	Cast Iron	
Electro Negative	Carbon Steel	
	Aluminium alloys	
	Zinc	
	Magnesium	

Source: NPL

Stress Corrosion Cracking

- Requires both tensile stress and a specific corrosive medium
- Highly specific to alloy, environment and exposure conditions
- Stresses may be due to fabrication or service
- Coatings can exclude the environment

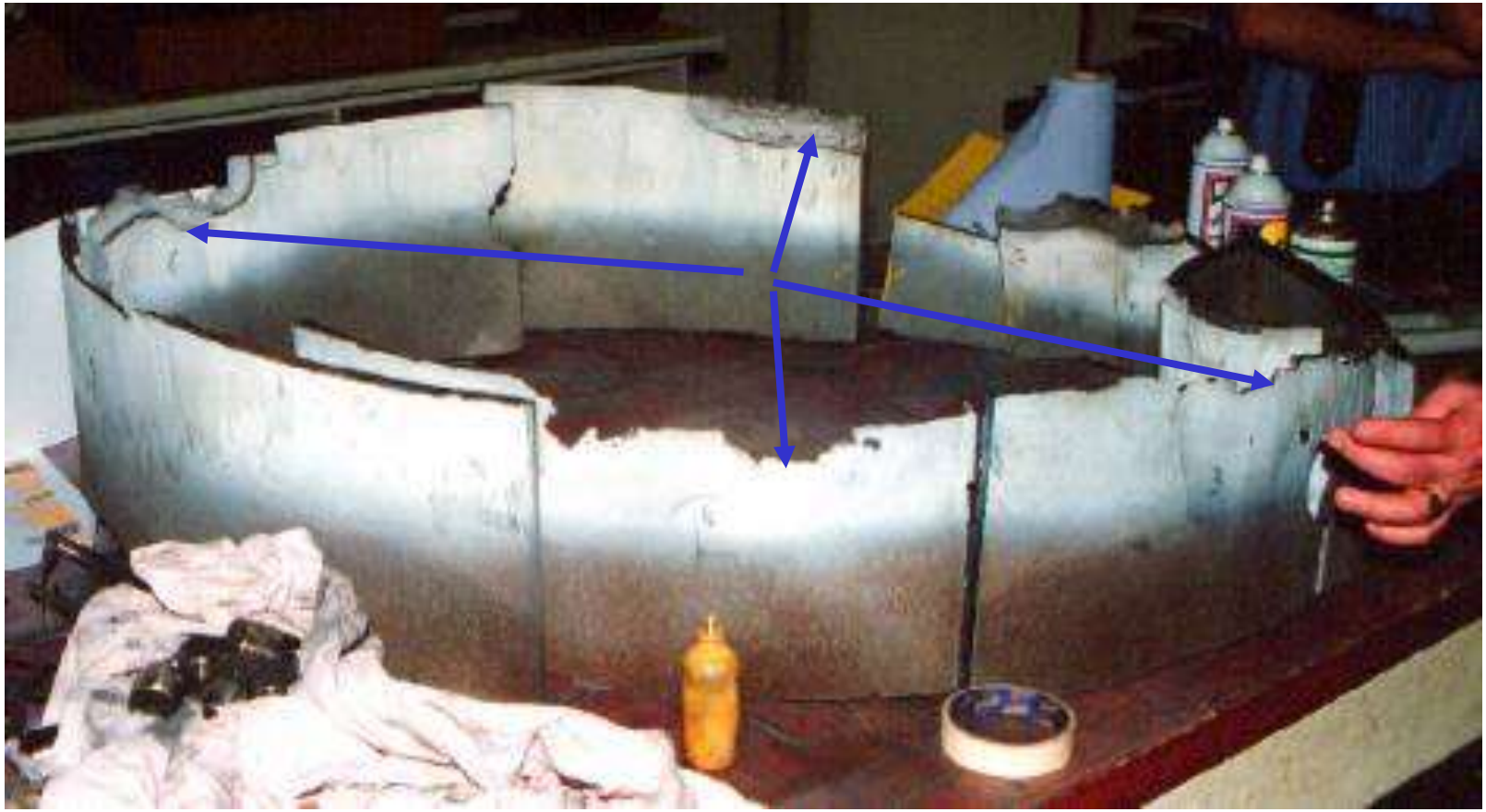
Stress Corrosion Cracking



Corrosion Fatigue

- Caused by a combination of cyclic stress and a corrosive environment
- Hard to distinguish from plain fatigue
- Coatings can exclude the environment
- Techniques that improve plain fatigue resistance can also help with corrosion fatigue - e.g. carburising, nitriding, shot peening

Corrosion Fatigue



Other Forms of Corrosion

- EROSION-CORROSION
  - synergy of erosive and corrosive decay
- CAVITATION
  - collapsing air bubbles erode surface
- GRAPHITIC CORROSION
  - preferential attack in grey cast iron
- GALLING
  - local cold welding and tearing (stainless steels)
- FRETTING
  - small movements generating fine debris

Reinforcement Corrosion

Reinforcement Corrosion

Reinforcement Corrosion

Cost of Corrosion - Studies

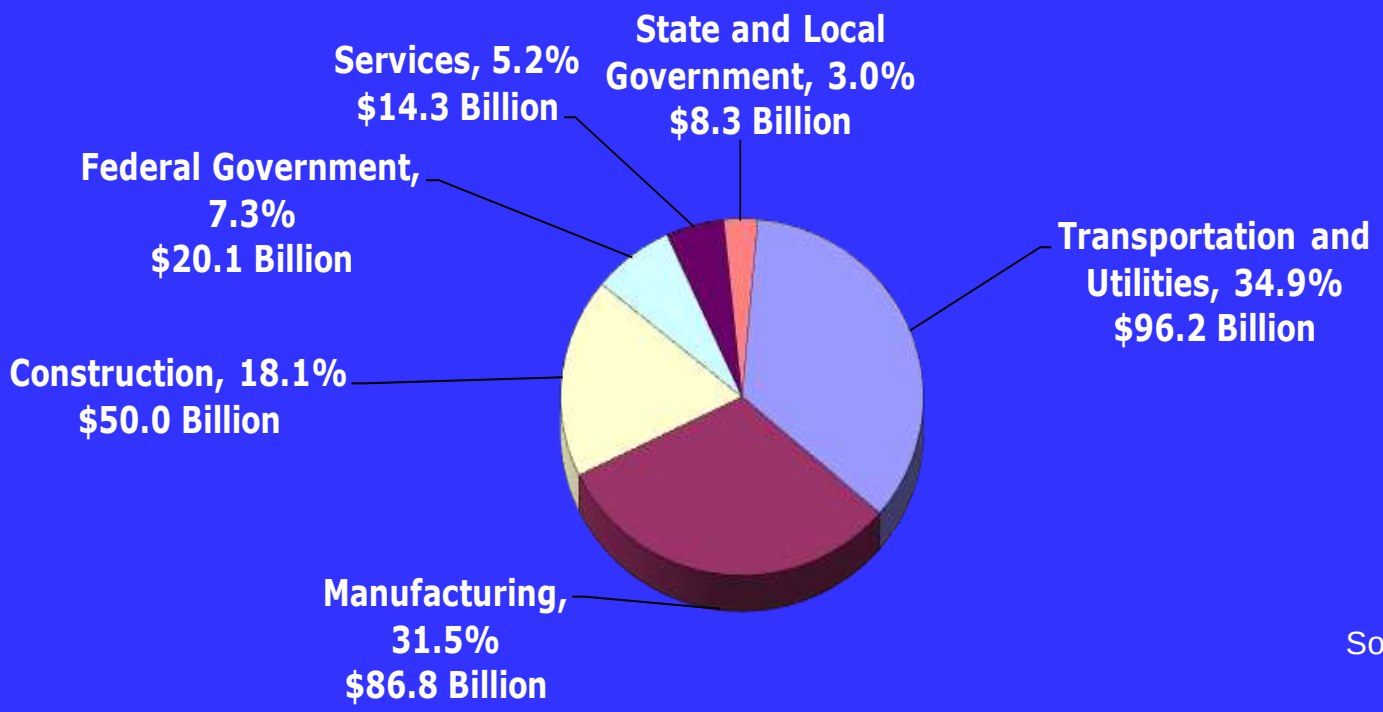
• 1950 H.H. Uhlig, US	2.1% of GDP
• 1970 T.P. Hoar, UK	3.5% of GDP
• 1974 Japan Study	1.2% of GDP
• 1975 Battelle/NBS, US	4.5% of GDP
• 2003 NACE, Global	3.4% of GDP

Cost of Corrosion – World-Wide

Economic Regions	Agriculture CoC US$ billion	Industry CoC US$ billion	Services CoC US$ billion	Total CoC US$ billion	Total GDP US$ billion	CoC % GDP
United States	2.0	303.2	146.0	451.3	16,720	2.7%
India	17.7	20.3	32.3	70.3	1,670	4.2%
European Region	3.5	401	297	701.5	18,331	3.8%
Arab World	13.3	34.2	92.6	140.1	2,789	5.0%
China	56.2	192.5	146.2	394.9	9,330	4.2%
Russia	5.4	37.2	41.9	84.5	2,113	4.0%
Japan	0.6	45.9	5.1	51.6	5,002	1.0%
Four Asian Tigers + Macau	1.5	29.9	27.3	58.6	2,302	2.5%
Rest of the World	52.4	382.5	117.6	552.5	16,057	3.4%
Global	**152.7**	**1446.7**	**906.0**	**2505.4**	**74,314**	**3.4%**

Source: NACE

Cost of Corrosion – USA



Source: NACE

The State of the Nation (ICE) Assessment of Condition of UK Infrastructure

Category	Condition Grade	Change	Sustainability Grade
Overall	**C-**	↑	**C**
Energy	D+	↑	D
Waste Management	C-	↑	D+
Water & Wastewater	B	↓	C+
Flood Risk Management	C	↓	B
Rail	C	–	D+
National Roads	C+	–	D
Local Transport	C	–	C-
Seaports	B-	–	C+
Airports	C+	–	D+

A = Good, B = Fair, C = Average, D = Poor, E = Bad

Corrosion Awareness Day 2017

American Infrastructure Report Card by American Society of Civil Engineers

Category	Condition Grade
Roads	D
Bridges	C
Transit	D+
Rail	C-
Aviation	D+
Power Grid	D
Drinking Water	D-
Waste Water	D-
Dams	D

A = Exceptional, B = Good, C = Mediocre, D = Poor, E = Failing

Corrosion Awareness Day 2017

22 INTERNATIONAL

70,000 bridges in America are riddled with building faults

ED HARRIS

MORE THAN 70,000 bridges across America are rated structurally deficient like the one that collapsed in Minneapolis, killing at least four people, it emerged today.

Engineers estimate repairing them all would take at least a generation and could cost £100 billion.

The warning came as US federal officials alerted states to inspect immediately all bridges similar to the bridge in Minnesota which collapsed during rush hour, sending dozens of people and vehicles plunging into the Mississippi river.

Rescuers were today waiting for dawn before they could resume the grim search for bodies.

At least four people are confirmed dead with up to 30 missing after around 60 vehicles were hurled into the water when part of the I-35W bridge gave way on Wednesday evening. Rescue officials said they expected the death toll to rise.

Hospitals said they treated 38 people, mainly for broken bones and head and spinal injuries.

Minneapolis mayor Raymond Thomas Rybak said: "Sadly and tragically, we don't believe there are people who are alive in the river. That means we are going to be very, very careful not to risk anything with the divers who are there, so we will be cautious in that regard."

President Bush said the federal government must "respond robustly" to help the people of Minnesota recover and rebuild the bridge as quickly as possible.

Mr Bush will travel to the scene tomorrow. His wife, Laura, was today visiting Minneapolis to meet victims.

The collapse has focused American attention on its ageing infrastructure, particularly bridges, which carry more than 300 million vehicles a day.

It is unclear how many of the spans pose actual safety risks. Federal officials alerted all states last night to immediately inspect similar bridges.

Transportation Secretary Mary Peters said: "Even though we don't know what caused this collapse, we want states to immediately and thoroughly examine all similar spans out of an abundance of caution."

The Minneapolis bridge was built in 1967, rose 64 feet above the river and stretched 1,100 feet. It was built with a single 458ft steel arch to avoid the need for piers that might interfere with river navigation.

There are 761 such steel-deck truss bridges, according to highway officials. The Federal Highway Administration said five years ago that addressing the backlog of bridge repairs would cost at least £30 billion.

Tons of concrete crashed into the water as the structure crumbled. Injured people waited for rescue as vehicles dangled off the crumpled concrete and smoke billowed into the sky from the wreckage of a lorry. Some people managed to swim to safety.

"The bridge started falling, cars were flying everywhere and I saw the water coming up," said Catherine [illegible] rich, whose [illegible] up in the water. [illegible] 30 children [illegible] safety, with [illegible] injuries, from [illegible] bus that clung [illegible] of a collapse [illegible] over the river.

Prayers: mourners at a Minneapolis church service for the bridge victims

Search: rescuers beam lights into the Mississippi from another

To Conclude

- Corrosion is a costly business in terms of:
  - Money
  - Resources
  - Energy
  - Lives

To Conclude

- Corrosion is a costly business in terms of:
  - Money
  - Resources
  - Energy
  - Lives
- While it cannot be totally avoided, it can be controlled
- Corrosion control is a major industry worldwide
  - and not a bad way to make a living

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THANK YOU FOR YOUR ATTENTION
ANY QUESTIONS?