Structural Steel – Are You Getting What You Need?
or “When Grade A is not A-grade”

Engineers Australia, Risk Engineering Society
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OVERVIEW

- Tower case study, Part 1 – What can go wrong
- What does ‘strength’ mean?
- How can you increase ‘strength’?
- How is steel specified?
  - Historical developments
  - International variations
- Statistical variations
- Tower case study, Part 2 – Let me count the ways
- How do we protect ourselves?
  - Specifying standards
  - Verifying the documentation
TOWER CASE STUDY, Part 1

- In 2010, installation of steel lattice towers
  - AS 3995-1994 Design of steel lattice towers and masts
  - Steel angle, 200x200x20 mm, supplied from overseas

- Foundation pull-out tests
  - In two cases, instead of foundation failing, the steel failed at 20%–30% of expected yield load
  - Suggested the steel severely embrittled & weakened
  - Various theories – e.g. hydrogen embrittlement
  - Owner engaged UQMP to investigate the cause
    - Stage 1: Basic metallurgy, whether hydrogen embrittlement, fracture mechanics calculations
    - Stage 2: Systematic experiments correlating full-scale test data with detailed laboratory trials
Tower angle steel

- For strength without excessive section thickness, specified an elevated-strength structural steel
  - With yield strength nominally 400 MPa
- Specified to JIS G3101 grade SS540
  - Similar to AS/NZS 3678 grade 400
- What does ‘grade SS540’ or ‘grade 400’ mean?
- In Australian terminology:
  - Nominal strength grade designation refers to approx yield strength in MPa, rounded to nearest 50 MPa
  - Numerically correct only for thin sections, lower for thick
  - In AS/NZS 3678, plate thicknesses 20–32 mm, grade 400 specified to have yield strength 360 MPa minimum
Fracture surfaces

- Very brittle, planar fracture surface

- Small pre-existing defects
Stage 1 investigation

- Charpy impact tests
  - Confirmed that the steel is very brittle
  - Embrittlement not reversible by hydrogen baking treatments, so cannot be attributed solely to hydrogen

- Fracture mechanics calculations
  - Small pre-existing cracks not enough to explain failure; would not have failed if steel not severely embrittled
  - Embrittlement worse at time of failure than now
  - Possibly some role from hydrogen, diffused out

- Basic metallurgy
  - Chemical composition, microstructure and hardness all much as expected, almost within specification
Charpy V-notch impact tests

- Measured data compared to expected
  - For low-carbon structural steel, normally expect Charpy V-notch impact energy \(\sim 100 \text{ J}\) at room temperature
  - AS 3678 grade 400 specifies CVN avg \(\geq 40 \text{ J}\) at \(-20^\circ\text{C}\)
  - Measured on as-received sample: avg \(8 \text{ J}\) (8.1 \(\pm\) 0.4 J)
  - After baking 24hrs at 200\(^{\circ}\text{C}\): avg \(10 \text{ J}\) (10.0 \(\pm\) 1.0 J)

- This represents very severe embrittlement, very unexpected for this type of steel

- SEM examination of fracture surface showed mostly transgranular cleavage fracture mode (+ small amount of intergranular)
SEM fractography
### Chemical composition

- Measured on failed sample versus specifications

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>V</th>
<th>Al</th>
<th>CE*</th>
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<td>Measured</td>
<td>0.17</td>
<td>1.32-1.39</td>
<td>0.17-0.18</td>
<td>0.03-0.04</td>
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<td>0.02</td>
<td>&lt;0.005</td>
<td>0.40-0.41</td>
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<tr>
<td>JIS G3101 gr SS540</td>
<td>&lt;0.30</td>
<td>&lt;1.60</td>
<td>&lt;0.040</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>AS 3678 gr 400</td>
<td>&lt;0.22</td>
<td>&lt;1.70</td>
<td>&lt;0.55</td>
<td>&lt;0.030</td>
<td>&lt;0.040</td>
<td>&lt;0.10</td>
<td>&lt;0.100</td>
<td>&lt;0.48</td>
</tr>
</tbody>
</table>

* Carbon equivalent \( CE = C + \frac{Mn}{6} + \frac{(Cr+Mo+V)}{5} + \frac{(Ni+Cu)}{15} \)

- Impurities S & P higher than normal – ‘dirty’ steel
- Deoxidants Si & Al low – possibly ‘semi-killed’ steel
Hypotheses

- Chemical composition borderline – not sufficient deviation to provide clear explanation for failure
- Hydrogen embrittlement (HE) eliminated*
- Temper embrittlement (TE) and tempered martensite embrittlement (TME) not relevant
- Strain-age embrittlement (SAE) seemed only mechanism consistent with available evidence
  - Known to occur in cold-worked steels subjected to galvanising thermal cycles (typically 450-460°C)*
  - Occurs more readily in semi-killed than fully-killed steels
  - Text-book examples of SAE start with galvanised plates in TV mast and other tower components
WHAT DOES ‘STRENGTH’ MEAN?

- Most national standards for structural steels use designation based on ‘strength’ of the steel

- But ‘strength’ can mean different things:
  - Yield strength (YS) – value of applied stress at which permanent deformation occurs, in smooth lab specimen
  - Ultimate tensile strength (UTS) – value of stress at which fracture occurs, in smooth lab specimen
  - Notched fracture strength (NFS) – stress at which fracture occurs in a body containing pre-existing cracks

- National standards:
  - In AS/NZS 3678, ‘grade 400’ means YS nom 400 MPa
  - In JIS G3101, ‘grade SS540’ means UTS min 540 MPa
Steel strength grades

- Strength grades in national standards:
  - AS/NZS 3678: Grade 400 means YS nom 400 MPa
    Plate 20-30mm: YS min 360 MPa, UTS min 480 MPa
  - JIS G3101: Grade SS540 means UTS min 540 MPa
    Plate 16-40mm: YS min 390 MPa, UTS min 540 MPa
  - GB/T 1591: Grade Q420 means YS min 400 MPa, UTS 520-680 MPa

- In the tower case (spec JIS G3101 grade SS540), measured material properties:
  - YS: Eleven samples 407–536 MPa, one sample 371 MPa
  - UTS: All twelve samples 562–711 MPa

- But what about notched fracture strength?
Notched fracture strength

- Standards do not specify notched fracture strength values – depends on size & sharpness of notch
- In stage 2 of tower investigation, full-scale tests performed on 116 lengths of steel angle
  - Maximum load 3000 kN (306 tonne)
  - Corresponding max applied stress 320 MPa (< YS)
  - 95 lengths (82%) passed test – did not fracture
  - 21 lengths (18%) failed – fractured during test, at applied stress values 141–314 MPa (average 215 MPa)
  - Failures (at <YS) attributed to combination of:
    - Presence of stress-concentrating pre-existing cracks;
    - Embrittlement of the steel
Practical strength

- Notched fracture strength decreases when steel is ‘brittle’, i.e. when ductility & toughness are low

- Measures of ductility and toughness
  - Ductility: elongation before failure for smooth specimen
  - Toughness: Charpy V-notch impact energy, or $K_{IC}$ plane strain fracture toughness

- Ductility & toughness tend to decrease when yield strength increases
  - Be cautious with standards that specify only YS or UTS – may permit steel that is brittle, low NFS

- Practical strength
  - Actual stress at which failure will occur in service
  - Whichever of YS or NFS is lower
How can you increase ‘strength’?

- A brief lesson on physical metallurgy
- Strengthening mechanisms in steel
  a) Solid solution strengthening by ‘substitutional’ alloying elements (such as Mn, Ni or Cr) in solution
  b) Solid solution strengthening by ‘interstitial’ alloying elements (such as C, N or B) in solution
  c) Dispersion strengthening by iron carbides (Fe₃C/pearlite)
  d) Work hardening – cold deformation, causing a massive increase in number & tangling of ‘dislocations’
  e) Grain refinement
  f) Dispersion strengthening by alloy carbides (Mo, Nb, V)
  g) Alloying for ‘hardenability’ + quenching to ‘martensite’ (usually followed by ‘tempering’)
Effect of incr. YS on toughness

- The above are methods of increasing YS & UTS
- But might **decrease** NFS or **practical** strength
  - Most of these strengthening mechanisms **decrease** ductility and toughness, hence decrease NFS
  - **Work hardening** particularly bad for ductility & toughness
  - **Grain refinement** is the only strengthening mechanism that improves ductility & toughness
- To achieve elevated YS (>400 MPa) without loss of toughness, use combinations of a), b), e) & f)
- To achieve very high YS (>600 MPa) without loss of toughness, use alloying for hardenability plus quenching & tempering, g)
HOW IS STEEL SPECIFIED?

- We have seen that specifying steel by ‘strength’ alone can lead to unexpected failures
- What we call ‘structural steel’ or ‘mild steel’ or ‘low-carbon steel’:
  - Very vague terminology*
  - Typically specified primarily by YS or UTS
  - National standards may or may not specify some measure of ductility and/or toughness
  - Standards may or may not specify maximum permissible levels of those impurity elements known to promote decreased toughness
  - May or may not specify production methods that can influence toughness
  - May or may not specify ‘quality’ in any way
Chemical composition of steel

- Steel is an alloy of iron (Fe) and carbon (C)
- Carbon may be as low as 0.01% or as high as 2% but for structural steels usually 0.10–0.25%
- Steels always contain numerous other elements
  - Silicon (Si), manganese (Mn), chromium (Cr), nickel (Ni), copper (Cu), molybdenum (Mo), cobalt (Co), tungsten (W);
  - Phosphorus (P), sulphur (S), nitrogen (N), oxygen (O);
  - Aluminium (Al), vanadium (V), niobium (Nb), titanium (Ti);
  - Boron (B), calcium (Ca), zirconium (Zr), cerium (Ce)
  - Lead (Pb), bismuth (Bi), tin (Sn), antimony (Sb), arsenic (As)
- Some improve properties, others potentially harmful, all must be managed during production
Effects of composition

- Alloying elements, incidental elements and impurities – can be beneficial or harmful, or both!
  - See following slides for some details (skip over in talk)

- Be cautious when you read web sites (and even text books) on the effects of various alloying elements

- For example the effect of chromium:
  - You will see it written that Cr “increases strength”
  - But in such documents, ‘strength’ almost always means YS & UTS (smooth specimens), not NFS (notched)
  - You may also see it written that Cr “increases toughness”, but this depends strongly on the specific heat treatment and on carbon content
Roles of chemical elements

C  The most important alloying element in steel. Increases yield strength and hardness; Decreases ductility and toughness; Decreases weldability; Tends to segregate

Mn  Increases YS; Aids grain refinement, which improves toughness; Combines with S, which reduces risk of solidification cracking

Si  Tends to increase YS and hardness, but may reduce ductility; Is added as a deoxidising agent

P  A harmful impurity element, though sometimes added to improve atmospheric corrosion resistance (e.g. WR 350); Increases YS and hardness; Decreases ductility & toughness; Has strong tendency to segregate
Roles of chemical elements

S  Harmful impurity, though sometimes added to improve machinability; Significantly reduces fracture toughness; Forms low melting point iron sulphides and hence promote solidification cracking; Readily captured by Mn which helps to minimise its negative effects

O  Generally harmful; Can form low melting point iron oxides and hence promote solidification cracking; Must be removed during steelmaking

N  Causes serious embrittlement if it remains in solid solution or forms iron nitrides; Partly responsible for strain age embrittlement
Roles of chemical elements

Cr  Increases YS; Greatly improves corrosion resistance; May either improve or reduce toughness

Ni  Increases YS; Usually said to improve toughness

Cu  Increases YS; May impart weathering resistance; May improve toughness

Mo  Increases YS; Greatly improves resistance to pitting corrosion; Improves resistance to solidification cracking; May either improve or reduce toughness

B   Added in very small amounts (0.0005%); Increases hardenability in Al deoxidised steels by retarding transformation to ferrite & bainite; Improves toughness in low O & N steels; More than the optimum amount can have an adverse effect
Roles of chemical elements

**Al**  Used as deoxidant; Reacts with nitrogen to form nitrides; Assists grain refinement by controlling grain growth when reheated; Excess Al can cause brittleness

**Ti**  Strongly forms carbides; Also forms nitrides; Aids in control of grain size, effective at high temperatures, and hence can improve both strength and toughness

**Nb**  Aids in control of grain size by raising the temperature at which the steel recrystallises

**V**  Aids control of grain size, particularly at lower temperatures
Historical context

- 50 years ago, almost all steel used in Australia was produced in Australia
  - Steels were produced from blast furnace iron by the open hearth process, and cast into ingots
  - Steel available as semi-killed or fully-killed* product
    - *Removal of dissolved oxygen by Si and/or Al
  - Ingots were then rolled or forged into plate and sections

- The quality reflected capability of process route
  - Australian Standards reflected the properties and quality of Australian steels
  - Australian design standards made use of the available steels and the known properties
Historical context

- Today most Australian-made steel is produced by basic oxygen steelmaking from blast furnace iron
  - All steel is fully killed
  - Continuously cast into blooms or slabs
- Much of steel used in Australia today is imported
  - Many countries; do not use Australian Standards
  - Most countries have their own national standards, and/or use international standards such as ISO
  - We cannot assume that apparently similar grades are equivalent or perform as well
  - Even if the overseas steel was ‘better’, it is important that we know precisely what we are buying
Historical developments

- Steelmaking practices and quality control have evolved in the last 100 years
  - National standards, incl Australian standards, have evolved in parallel with these developments
  - However, actual capability has typically been ahead of the minimum quality standards specified in standards

- See Appendix 1, Historical Development
  - Development of Australian Standards from 1920 to 2010
  - Maximum permissible sulphur
  - Maximum permissible phosphorus
  - Notch ductility requirements
  - Other composition, quality and performance specifications
### Historical developments

- **Maximum permissible sulphur & phosphorus**

<table>
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<tr>
<th>Year</th>
<th>AS</th>
<th>Sulphur</th>
<th>Phosphorus</th>
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<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>1928</td>
<td>A1</td>
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<tr>
<td>1965</td>
<td>A149</td>
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<tr>
<td>1966</td>
<td>A152</td>
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<tr>
<td>1980</td>
<td>1204</td>
<td>0.03</td>
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</tbody>
</table>

- Note that specified limits depend on intended application of the steel; not all current standards as stringent as AS1204
Historical developments

- Notch ductility – Specs introduced 1965, 1966
- AS A149 – 1965, Mild steel for general structural purposes
  - Introduced requirements for minimum Charpy V-notch impact energy at various test temperatures
  - Min 27 J absorbed energy at 0°C, -15°C, -30°C and -50°C
  - The higher quality (lower temperature) grades also required to be made from fully killed steels, with Si specified to be between 0.10 and 0.35%
- AS A151 – 1966, Structural steel of high yield stress (welding quality)
  - Min 27 J absorbed energy at +15°C, 0°C, -15°C & -30°C
Are you getting what you need?

- At UQMP we investigate many failed components
- Becoming increasingly concerned that some imported steels not up to expected quality
- Supplier may claim the steel is a grade equivalent to the grade specified on the design drawings, but what is ‘equivalent’?
- Do you, as owner, designer, specifier, certifier, operator (or user!), know whether this equivalence can be relied upon?
- What can we do to protect ourselves against inadequate quality product?
Are you getting what you need?

- What is important?
  - Yield strength? (Average? Sample minimum? Population min?)
  - Notch ductility?
  - Chemical composition?

- To be sure of “getting what you need”, you must pay attention to the following areas:
  - Know what is important (and what can be left to chance)
  - Write appropriate, sufficiently explicit specifications into your drawings and contract documents
  - Demand correct documentation, and read it!
  - Strategies for verifying compliance
  - Strategies for rejecting non-compliant product before it’s too late (before rejection would derail your project)
INTERNATIONAL VARIATIONS

Ways in which international standards may differ when specifying steel:

- Code designation based on strength – YS or UTS
- Dealing with statistical variations in strength
- Whether or not they contain different ‘quality’ grades (typically specifying notch ductility)
- Whether or not they specify chemical composition
- Whether or not they stipulate processing routes

Yield strength vs tensile strength

- Have already seen an example of this
- Designating by YS or UTS is a relatively trivial distinction – important, but should be easy
Yield strength vs tensile strength

- Note that simply ‘tensile strength’ is the currently accepted terminology for UTS.
- In AS/NZS 3678, ‘grade 400’ means **YS nominally 400 MPa**
  - For plate 12-20 mm thick, spec minimum **YS 380 MPa**
  - For plate 20-32 mm thick, spec minimum **YS 360 MPa**
- In JIS G3101, ‘grade SS400’ means **UTS minimum 400 MPa**
  - For plate 16-40 mm thick, spec minimum **YS 235 MPa**
  - You would get a rude shock if you assumed that ‘SS400’ meant YS 400 MPa!
Statistical variations

- In any population of products, there is a statistical scatter in properties
  - A sufficiently large sample (number of specimens/tests) must be performed to ensure that the sample mean approximates the population mean.

- International standards may differ in the way they specify statistical validation of test results.

- However, this is a bigger issue when suppliers attempt to claim that their product is “equivalent” to a given standard, based on a single test result or single test certificate.
  - They could be selective in which test results they show.
“Grading by selection”

▫ Attempts by a supplier (onseller) to sell a batch of steel as compliant with a given grade:
  ▪ Based only on the results of some tensile tests
  ▪ Without a manufacturer’s mill certificate certifying that their product satisfies all requirements of the standard grade (e.g. AS/NZS 3679.1 - Grade 350)

▫ Two forms of this practice:
  ▪ Grading by test: Supplier does not have a mill certificate, but has obtained some tensile tests from the batch
  ▪ Up-grading: Supplier has a manufacturer’s mill certificate stating one strength grade (e.g. grade 300) but supplier claims that the actual batch meets the requirements of a higher strength grade (e.g. grade 350)
Grading by test

- Supplier does not have a mill certificate, but has obtained one or more tensile tests from the batch
  - Claims that the batch complies with the strength grade indicated by the tensile test results

- Actual case (courtesy of Australian Steel Institute):
  - A steel fabricator had a batch of steel sufficient for the structures on a project
  - Did not have a mill certificate
  - Fabricator took one length of steel from the batch and had a tensile test performed by a reputable test lab; measured yield strength was 315 MPa
  - Fabricator asked the engineer on the project “Will you certify it as Grade 300 steel to AS 4100?”
Grading by test

- In a typical steel mill, single heat 100+ tonnes
  - Rolled to give ~3000m of product
  - Statistical distribution of strengths

- Reputable steel mill will grade the steel in accordance with minimum strength of population

- Not reliable to represent steel as grade 300 on basis of a one-off test

This is still Grade 235 steel and must not be designated as, certified as, or sold as Grade 300
Up-grading

- Supplier has a manufacturer’s mill certificate stating one strength grade (e.g. grade 300)
- But tensile test values on that certificate suggest that the batch might meet the requirements of a higher strength grade (e.g. grade 350)
Up-grading

- Supplier has a manufacturer’s mill certificate stating one strength grade (e.g. grade 300)
- But tensile test values on that certificate suggest that the batch might meet the requirements of a higher strength grade (e.g. grade 350)

> This is Grade 300 steel

> “All six YS values are above 350 MPa, so can I design it as Grade 350 steel?”
Up-grading

- Typical distribution of YS values of different batches of section made to AS/NZS 3679.1- Grade 300
Up-grading

Yield Strength (MPa) vs. Frequency

ReH
MPa

375
360
365
370
365
365

300 MPa

Frequency

0 10 20 30 40 50 60

310 320 330 340 350 360 370 380
Up-grading

- Yield strengths all above 300MPa, and go up as high as 400MPa in a normal Gaussian distribution
  - Results shown on the test certificate came from the area shaded blue on the diagram
  - But other results will go higher, others lower
  - All results are above 300 MPa, as the standard requires, but almost half will be under 350 MPa

- So, despite the fact that the results on the test certificate were all above 350 MPa, this is still Grade 300 steel and must be designed as such
Grading by selection

- A small sample of test results
  - Likely not to capture the full distribution of values within a given batch
  - Even more probably will not capture the full distribution of values within a given mill heat
  - Certainly does not capture the distribution of values produced from a series of heats over time

- Reputable steel mills issue certificates with steel grade based on their production over time
  - Australian: 100% of product meets this standard
  - Some others: 95% of product meets this standard
Grading by selection - Conclusion

- Hence your small batch of steel:
  - Purported to comply with a given grade based on a few test results ...
  - Almost certainly is **not** of equivalent quality to the typical production of a mill which certifies their product to this grade

- Existing or future legislation and Standards:
  - Will stipulate that steel grade can **ONLY** be determined by the kind of statistical ‘type testing’ practiced by reputable mills
MEASURES OF ‘QUALITY’

- Within a given strength grade, ‘quality’ can be assessed by:
  - Notch ductility
  - Chemical composition

- Notch ductility
  - Usually assessed by Charpy V-notch impact test
  - Test temperature affects energy absorbed
  - Minimum acceptable energy at a designated temperature
    - e.g. CVN ≥ 27 J at 0°C; CVN ≥ 27 J at -30°C
  - Maximum acceptable value of ductile-to-brittle transition temperature (DBTT = temperature at which a designated acceptable energy is crossed)
    - e.g. 27 J DBTT ≤ -15°C
When ‘grade A’ is not ‘A-grade’

- Beware of assumptions
  - Saw case where Japanese standard was designated by UTS while Australian standard was designated by YS
  - One is not better than the other, just different
  - Don’t assume; be aware

- In casual English the term ‘A-grade’ means ‘very high quality’
  - But this is just colloquial, not standard terminology

- Chinese standard GB/T 1591 – 2008
  - Strength grades according to nominal yield strength
  - e.g. Q420 specified as minimum YS:
    - 420 MPa for plate ≤ 16 mm thick
    - 400 MPa for plate 16-40 mm
    - 380 MPa for plate 40-63 mm
When ‘grade A’ is not ‘A-grade’

- Chinese standard GB/T 1591 – 2008
  - Strength grades according to nominal yield strength
  - Quality grades A, B, C, D, E according to achievement of CVN 34 J at various temperatures
  - Unrelated to strength grades A to F in AS A33 & AS A135

For example nominal YS 400 MPa steels:

<table>
<thead>
<tr>
<th>GB/T 1591</th>
<th>Grade Q420</th>
<th>AS/NZS 3678</th>
<th>Grade 400</th>
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<tr>
<td>Quality Grade</td>
<td>CVN</td>
<td>Impact Desig</td>
<td>CVN*</td>
</tr>
<tr>
<td>A</td>
<td>Not specified</td>
<td>L15</td>
<td>≥27 J at -15°C</td>
</tr>
<tr>
<td>B</td>
<td>≥34 J at +20°C</td>
<td>L20</td>
<td>≥27 J at -20°C</td>
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</table>
When ‘grade A’ is not ‘A-grade’

- Not worse or better, just different
  - Like the issue with Japanese vs Australian designations, it is just a matter of understanding the terminology
  - We are not implying there is anything wrong with GB/T 1591 – 2008
  - In fact quite a good standard, and if strength grade Q420 quality grade C or D had been specified & complied with, tower failure would probably have been avoided

- Standards from different countries
  - Don’t assume that a standard from a mature industrialised region (Japan or Europe) necessarily better
  - Take responsibility to look at the detail and select a standard suitable for the project
“Let me count the ways”

Stage 2 investigation
- Full-scale tensile testing on 116 lengths of angle section
- Correlation between full-scale tensile test results and laboratory test results
- Detailed metallurgical investigation

Full-scale tensile tests
Batch problems

Stage 2 investigation
- Correlation between full-scale tensile test results and laboratory test results

Batch problems
- Full-scale: 95 samples passed the 3000 kN load, 21 failed at lower loads
- Distribution of failures revealed strong batch influence
- Failures only occurred in specific lengths (but no monotonic relationship between NFS and length)
- All 21 of the failed samples carried the manufacturer’s label “SSHT 7/8”, while no failures occurred in samples labelled “SSHT 7” or “SSHT 8”
Batch problems

SSHT 8
- Manufactured 2008?
- No failures

SSHT 7/8
- Mfr 12/2007-1/2008?
- 21 failures

SSHT 7
- Manufactured 2007?
- No failures
Batch problems

- Manufacturer’s labels and full-scale results used to guide selection of samples for laboratory testing
  - Steel chemistry and properties measured in laboratory showed clear batch dependence
  - Correlating well with the results of the full-scale tests

- Batch SSHT 8
  - Good consistency of properties in lab tests (correlating with fact that none of this batch failed in full-scale test)
  - Tensile strengths within mid-range specified by GB/T 1591 grade Q420
  - Tensile elongation results were good
  - Charpy V-notch impact results excellent (99 to 116 J)
Brittle batch SSHT 7/8

- **Mechanical Properties**
  - Wide scatter of properties in lab tests (correlating with wide scatter in full-scale test results)
  - Samples that had failed in full-scale test and then subjected to detailed laboratory tests showed:
    - Extremely low Charpy impact energies (5 to 8 J)
    - Yield strengths considerably **higher** than usually expected for grade 400 steel
    - In several cases tensile strengths **above** the maximum permitted by GB/T 1591 Q420

- **Chemical composition**
Brittle batch SSHT 7/8

Chemical composition

- Elevated nitrogen (0.015 to 0.017%), at or above the maximum permitted by GB/T 1591 Q420
- Elevated phosphorus (0.028 to 0.041%), in four cases above maximum permitted by GB/T 1591 Q420 and in two cases above max permitted by JIS G3101 SS540
- Elevated sulphur (0.031 to 0.038%), in three cases above maximum permitted by GB/T 1591 Q420
- Most samples lacked any appreciable aluminium, indicating steels de-oxidised only with silicon instead of the more favourable Si-Al dual de-oxidation; Overall impression of steel with inadequate de-oxidation practice
Literature review

- Strain-age embrittlement?
  - Literature confirmed that the general phenomenon called “strain-age embrittlement” is the most plausible explanation for severe brittleness in steels of this type.
  - However, rather than focusing on elevated-temperature ageing step (galvanising), the literature places more emphasis on the chemistry, de-oxidation practice and cold deformation of the steel prior to ageing.

- Numerous undesirable parameters contributed:
  - Excessive N, S and P – all known to reduce toughness
  - Lack of elements to bind nitrogen (Al, Ti, V, Nb)
  - Lack of grain refinement by Al
  - Excessive yield strength and tensile strength
Critical experiments

- Collected evidence (lab property correlation, lit review & critical experiments) indicated severe embrittlement of batch SSHT 7/8 due combination of four unfavourable features of the steel

- Critical experiments indicated contributions:
  - Undesirable steel chemistry — ~35% of total embrittlement (DBTT shift)
  - Elevated grain size — ~16% of total embrittlement
  - Undesirable strengthening mechanisms — ~28% of total embrittlement
  - Ageing by galvanising — ~21% of total embrittlement
Standards

- Japanese standard JIS G3101, to which the steel was specified:
  - Clearly inadequate to prevent supply of steels suffering from this kind of embrittlement

- Chinese standard GB/T 1591-2008:
  - Appropriately specifies grades in regard to ‘quality’ and not merely yield strength
  - For the higher quality grades it specifies:
    - maximum acceptable N levels;
    - minimum acceptable Al levels;
    - max S & P levels lower than those permissible in JIS G3101;
    - minimum acceptable Charpy impact values

Australian & European standards
Diagnostics

- Evidence indicated most useful diagnostic tests for detecting actual or probable embrittlement:
  - Charpy V-notch impact testing
  - Spectrographic analysis of steel composition
- CVN by far the most reliable means of identifying steel sections at risk of brittle failure
  - Directly detects the metallurgical embrittlement that caused the 2010 failures
  - Should do so even for steel not yet galvanised
- Spectrographic analysis
  - Most practical diagnostic for existing structures
  - Strong correlation between composition and brittleness
Specifications for grade 400

- Recommended specifications & acceptance criteria
  - No single national standard addresses all factors needed to prevent brittleness in grade 400 steels
  - Representing best practice from comparison between JIS G3101, AS 3678, GB/T 1591 and EN 10025

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mandatory Rejection if does not comply</th>
<th>Warning Flag if does not comply</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVN (J)</td>
<td>≥ 34 J @ 0°C</td>
<td>≥ 34 J @ -20°C</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>≤ 0.012 wt%</td>
<td>≤ 0.009 wt%</td>
</tr>
<tr>
<td>Aluminium</td>
<td></td>
<td>≥ 0.009 wt%</td>
</tr>
<tr>
<td>Ratio Al/N</td>
<td></td>
<td>≥ 2</td>
</tr>
<tr>
<td>Sulphur</td>
<td>≤ 0.030 wt%</td>
<td>≤ 0.025 wt%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>≤ 0.030 wt%</td>
<td>≤ 0.025 wt%</td>
</tr>
<tr>
<td>Carbon</td>
<td>≤ 0.22 wt%</td>
<td>≤ 0.20 wt%</td>
</tr>
</tbody>
</table>
OVERVIEW

- Tower case study, Part 1 – What can go wrong
- What does ‘strength’ mean?
- How can you increase ‘strength’?
- How is steel specified?
  - Historical developments
  - International variations
- Statistical variations
- Tower case study, Part 2 – Let me count the ways
- How do we protect ourselves?
  - Specifying standards
  - Verifying the documentation
CONCLUSIONS

- Tower case study revealed the wide range of things that can go wrong
  - The embrittled steel showed almost every possible fault
  - However, any one of these faults could render structures at risk of unexpected failure
  - More commonly, problems are more subtle
  - Fewer problems from lower-YS steels

- The steel displayed problems which in most of the world had been solved 50 years ago
  - The need for scrutiny when sourcing from unknown manufacturers
  - The need for rigorous specification and procurement practices
CONCLUSIONS

- Existing standards may not specify all parameters that are required to prevent embrittlement
  - On safety-critical structures, should engage specialists who know what can go wrong, what is important
  - Development of better standards

- To be sure of “getting what you need”:
  - Write appropriate, sufficiently explicit specifications into your drawings and contract documents
  - Demand correct documentation, and read it!
  - Strategies for verifying compliance
  - Strategies for rejecting non-compliant product before it’s too late (before rejection would derail your project)
APPENDICES

- Too much detail to cover during the presentation, but may be useful to interested attendees
  - Appendix 1: Historical developments in Australian standards
  - Appendix 2: Comparison of international standards

- Other resources
  - Materials Australia short-course on Understanding Test Certificates
  - Australian Steel Institute and Steelwork Compliance Australia seminars and documents
  - OneSteel “Build with Standards” website
APPENDIX 1: Historical development

- Historical development of Australian standards for steel
- 1920: First Australian standard for structural steel
- 1928: AS A1 Structural Steel and Australian standard rolled steel sections for structural purposes
  - Part 1 Material Specification, Part 2 Dimensions etc.
  - Steel could be made by the open hearth process with S and P limited to 0.06%, or by Bessemer process with S limited to 0.06% and P 0.08%, but Bessemer steel not permitted for bridges, plates over 6mm, or rivets.
  - UTS 432 – 510 MPa; YS recorded but not specified
Historical development

- **1931: AS A1 revised**
  - No change to material properties

- **1937: AS A33 Plates for general engineering purposes**
  - Three grades D, E & F were introduced
  - Only S and P limits of 0.06% were imposed
  - YS specified as $\frac{1}{2}$ the actual UTS
  - UTS specified as

<table>
<thead>
<tr>
<th>Grade</th>
<th>UTS Range (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade D</td>
<td>432 – 510 MPa</td>
</tr>
<tr>
<td>Grade E</td>
<td>386 – 463 MPa</td>
</tr>
<tr>
<td>Grade F</td>
<td>324 – 401 MPa</td>
</tr>
</tbody>
</table>
Historical development

- **1955:** AS A33 Australian Standard Specification for carbon steel plates for general structural engineering purposes
  - Actual yield strength was specified
- **1956:** AS A1 Australian Standard Specification for Structural steel (excluding plates) and Australian standard rolled steel sections for structural purposes
  - While this edition included the 1940 revision and 1955 amendments, the compositional limits were as per 1937, and there was only one strength grade equivalent to Grade D as previously
Historical development

- **1965: AS A1** Dimension of hot rolled steel shapes and sections for structural purposes
  - This edition was a revision of part 2 of AS A1

- **1965: AS A147** General requirements for supply of hot rolled steel plates, sections, pilings and bars for structural purposes
  - This was a part revision of AS A1 – 1956, based on American standard ASTM A6

- **1965: AS A149** Mild steel for general structural purposes
  - Another part revision of AS A1 – 1956, specifying both chemical & strength properties, for both sections & plates
  - Only one grade specified
**Historical development**

- **AS A149 – 1965**

<table>
<thead>
<tr>
<th>Product</th>
<th>Thickness (inch)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates, sections and flat bars</td>
<td>≤ ¼</td>
<td>Bend test only</td>
<td>Bend test only</td>
</tr>
<tr>
<td></td>
<td>&gt; ¼ ≤ ¾</td>
<td>247</td>
<td>417 - 525</td>
</tr>
<tr>
<td></td>
<td>&gt; ¾ ≤ 1 ½</td>
<td>232</td>
<td>417 - 525</td>
</tr>
<tr>
<td></td>
<td>&gt; 1 ½</td>
<td>228</td>
<td>417 - 525</td>
</tr>
</tbody>
</table>
Historical development

  - Introduction of steels with improved resistance to brittle fracture and was based on BS 2762.
  - Specified two strength grades (A & B) and four levels of notch ductility based on 27 J absorbed impact energy at $0^\circ C$, $-15^\circ C$, $-30^\circ C$ and $-50^\circ C$
  - Apart from specifying C, Mn, S & P limits, the higher quality (lower temperature) grades were required to be manufactured from fully killed steels with silicon specified between 0.10 – 0.35%
  - [Note that the term ‘notch ductile steel’ implies that the steel has good ductility & toughness and hence good notched fracture strength (NFS)]
Historical development

 lamps: AS A157 Low and intermediate strength carbon steel plates of structural quality
- These two grades replaced the grades E and F from A33
- Maximum limits on S and P were lowered to 0.05%, and limits were placed on C and Mn

 lamps: AS A151 Structural steel of high yield stress (welding quality)
- Based on BS 968
- Only one strength grade was specified, but with options for notch ductility testing at 15°C, 0°C, -15°C and -30°C
- Maximum S and P lowered to 0.04%
- Limits placed on C, Mn, Si, Cr and grain refining elements
Historical development

- 1971: Significant rationalisation of standards but with some curious results
- A147 was revised concurrently with the introduction of new standards
- AS A186 Structural Steel – Ordinary weldable grades
  - Replaced A135, A149 and A151, i.e. the medium and higher strength and notch tough grades
  - Chemical composition limits were applied to all grades, along with limits on the C+Mn/6 for weldability
  - While grades were designated by the nominal yield strength in MPa, the strength was specified in kip/in² (where kip = 1000 pounds-force)
Historical development

- 1971: AS A187 Structural steel - Weather resistant weldable grades
  - Three strength grades of weathering-resistant structural steels introduced
  - Notch ductility specified at 0°C or -15°C
  - Compositional limits specified for 8 elements: C, Mn, Si, P, S, Cr, Cu and Ni

- 1972: AS 1204 & AS 1205 replaced AS A186 & AS A187 respectively, as fully metric standards with strengths given in MPa

- 1973: AS 1405 Carbon steel plates of structural quality
  - Metric standard replacing AS A157
Historical development

- **1980: AS 1204 Structural steels – ordinary weldable grades**
  - Replaced both AS 1204 – 1972 and AS 1405 – 1973
  - Considerable rationalisation of the number of grades
  - S and P limits for the new low strength formable grade were reduced to 0.03%

- **1980: AS 1205**
  - The number of grades specified in AS 1205 were also rationalised

- **1990: Another significant revision of structural steel standards.**
  - Standards for structural plate and sections separated
Historical development

1990: AS 3678 Structural steel – hot rolled plates, floor plates and slabs

- Included all the existing grades of plate, and reintroduced grades 300 and 400
- Composition limits for C, S and P reduced
- Limits were set on Nb, Ti and V, and distinction drawn between grain refining elements and micro-alloying elements
- The C + Mn/6 requirement was replaced by the IIW carbon equivalent for weldability
- 100% of Australian made steel complying with this standard was made from fully killed, fine grained continuous cast slab.)
Historical development

- **1990:** AS 3679 – 1990 Hot rolled structural steel bars and sections
  - Followed a similar philosophy to that of AS 3678
- **1991:** AS 3679 part 2 was issued to incorporate welded sections
- **1996:** AS 3678, 3679.1 and 3679.2 became AS/NZS standards
  - Some rationalisation of grades and sizes that were not popular
- By this time, all Australian steel was being produced in basic oxygen converters and was fully killed, fine grained and continuous cast
Historical development

2010: AS/NZS 3679.1 Structural steel Hot rolled bars and sections

- 1996 edition revised
- Strength grades rationalised to grade 300 and 350
- Including conventional notch ductile grades and a new seismic variation S0 with enhanced impact toughness
- Specifies compositional limits on C, Si, Mn, S, P, Cr, Ni, Mo, Cu, Ti, Nb, V and Al
- Limits on total of some elements in combination and the carbon equivalent as determined by IIW formula
- All steel must be made by basic oxygen or electric arc process and indicate the processing route, e.g. slab cast
- All testing must be conducted by third party accredited laboratories
APPENDIX 2: Comparison of Standards

Following slides compare Australian, European, Japanese and Chinese standards for hot rolled structural steels

Standards from four countries/regions considered:
- Australia: AS/NZS 3679.1-2010
- Europe: EN 10025-1, 2, 3, 4 - 2004
- Japan: JIS 3101 - 2004
Comparison of standards

- **Steelmaking**
  - AS/NZS – basic oxygen or electric arc
  - EN – at discretion of manufacturer but open hearth process is excluded
  - JIS – not stated
  - GB/T – converters or electric furnaces (out-of-furnace refining allowed)

- **Deoxidation practice**
  - AS/NZS – not stated but all Australian-made steels for structural purposes are fully killed and fine grained
  - EN – Method of deoxidation per parts 2 - 6 of standard
  - JIS – not stated
  - GB/T – May be rimmed, semi-killed or fully-killed depending on grade and quality
Comparison of standards

- **Grain refinement**
  - AS/NZS – not stated but all Australian-made steels for structural purposes are fully killed and fine grained
  - EN – Required grain size as per parts 2 - 6 of standard
  - JIS – not stated
  - GB/T – Quality class D shall have enough grain refining elements and shall be indicated in inspection documents

- **Limits on impurity elements**
  - AS/NZS
    - $S \& P \leq 0.04\%$
    - $N$ not specified but usually reported
Comparison of standards

Limits on impurity elements

- EN
  - S & P \leq 0.045\% for general products; 0.035\% for products with impact requirements; Product can be 0.01\% higher
  - N \leq 0.012\%; May be higher provided composition includes N-binding elements e.g. Al, which must be reported

- JIS
  - S & P \leq 0.050\% (0.040\% for highest strength grade)
  - N not mentioned

- GB/T 1591
  - S & P nominally 0.035\%; May be 0.045\% for quality grade A; 0.020/0.025\% for quality grade E
  - N \leq 0.015\% (Al required for quality grades)
Comparison of standards

- **Delivery condition**
  - AS/NZS – As-rolled
  - EN – May be supplied As-rolled, normalised or thermomechanical rolled at the discretion of the supplier unless otherwise specified
  - JIS – As-rolled
  - GB/T 1591 – Steels shall be delivered as hot rolled, controlled rolled, normalised, normalise rolled, normalised and tempered, thermomechanical rolled, or thermomechanical rolled and tempered
Comparison of standards

- **Strength grade designation**
  - **AS/NZS** – Designated by nominal *yield* strength rounded to 50 MPa
  - **EN** – Designated by specified minimum *yield* strength at ambient temperature in accordance with EN 10027-1:2005; Values decrease progressively for thicknesses above 16 mm
  - **JIS** – Designated by minimum *ultimate* tensile strength
  - **GB/T 1591** – Designated by minimum specified *yield* strength as per EN
Comparison of standards

- **Impact toughness designation**
  - AS/NZS – Low temperature impact toughness grades designated by suffix L or S
  - EN – Low temperature impact toughness grades designated by suffix J, K or L followed by a number indicating the test temperature
  - JIS – Not specified
  - GB/T 1591 – Designated by Quality Grade
    - Test temperature dictated by Quality Grade
    - Not required for Quality Grade A, nor for Grade B above strength grade 500
Comparison of standards

Quality

- AS/NZS – Standard requires manufacturer / supplier, purchaser or independent third party able to assess product for conformity to standard and not be dependant on quality management system (e.g. ISO 9001)
- EN – Conformity demonstrated by initial type testing, factory production control system conforming to ISO 9001 and product assessment
- JIS – In accordance with ISO 10474 Steel and steel products - inspection documents
- GB/T – Checking & acceptance of steel by manufacturer; Buyer entitled to check & inspect any items
  - Class A & B steel of same grade, same processing but different cast numbers are allowed to form mixed batches; Limits on carbon and manganese variations