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Design Note No. D1

Structural Steel for Low Temperature Applications

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By Anthony Ng

Introduction

This technical note provides guidance for the design of steel structures which are subjected to operating temperatures below zero degrees Celsius, in eg. Cold storage facilities.

There are two main areas of concern for low temperature applications:

1) The temperature at which the steel changes from tough, ductile behaviour to brittle behaviour, referred to as the transition temperature.
2) The detailing at the joints between members. It is primarily at joints that local stresses and defects can act as initiation points for brittle fracture.

Standard structural steel design is based on the premise that all elements of the structure are ductile, and brittle fracture is to be avoided. Therefore, ensuring that a steel structure remains adequately ductile during service is of the utmost importance. This requires selecting the appropriate steel for the low operating temperatures, and suitably detailing the connections. Failure to do so may lead to sudden brittle fracture and failure of the structure.

Code Provisions

Section 10 of AS 4100 – 1998 Steel Structures Code [1], and Appendix 10 of AS/NZ 1554 Parts 1 and 5 – Structural steel welding code [2] and [3], gives guidance on how to avoid brittle fracture. Table 10.4.1 of AS 4100 gives a list of minimum temperatures at which the listed structural sections and steel grades may be used with the standard design methods in the code, without requiring specific fracture mechanics design and testing. It recognises that standard InfraBuild universal and welded sections may be used in a wide range of low temperature applications. AS 4100 permits standard 300PLUS universal beams 360UB50.7 and smaller, and 410UB54 sections, to be used without fracture mechanics analysis in operating temperatures as low as -10°C. For 300PLUSL0 grade this temperature drops to -20°C. Tables 1a and 1b provides a summary of permissible design service temperatures based on Table 10.4.1 of AS 4100 for hot rolled and welded Australian made structural sections. The correct choice of steel for the intended operating temperature as per Table 1a and 1b will usually lead to the most efficient design.

Table 10.4.1 of AS 4100, and Table 1 of this note, have been derived from data on notch toughness characteristics of sections produced therefore are only valid in Australia for Australian made sections. Verification tests are required for imported or unidentified steels.

Section	Permissible Service Temperature	
	300PLUS®	300PLUSL0
Universal Beams		
610UB125 down to 460UB67	0	-10
410UB59.7	0	-10
410UB53.7	-10	-20
360UB56.7	0	-10
360UB50.7 & smaller	-10	-20
Universal Columns		
310UC158 down to 200UC52.2	0	-10
200UC46.2 & smaller	-10	-20
Parallel Flange Channels		
380PFC down to 250PFC	0	-10
230PFC & smaller	-10	-20
Angles		
ANGLES ≤ 6 Thick	-20	-30
ANGLES >6 and ≤ 12 Thick	-10	-20
ANGLES >12 and ≤ 20 Thick	0	-10

Table 1 Permissible service temperatures for ***Infra****Build Hot Rolled Sections*

The grades noted in Tables 1 are available with full test certificates from InfraBuild. Should you require any of these steel grades for your particular application it is advisable to contact your InfraBuild Supplier or InfraBuild Market Representative. Communication at the early stages of design is advisable, to ensure its availability and price, if applicable.

Temperatures not covered by AS4100 Section 10.4

Section 10.5 of AS 4100 permits design outside the provisions of Section 10.4, subject to fracture mechanics analysis and testing. A number of options are available to provide a satisfactory solution where this situation is presented to the designer. The most cost efficient solution will be a balance of material costs, testing costs, fabrication and inspection costs, and design effort.

In the design of structures where the section sizes or temperatures are outside the range of Table 10.4.1, early consultation with InfraBuild is strongly advised.

An alternative to using steels with very low transition temperatures is to invoke Clause 10.5 of AS 4100. This clause requires a fracture mechanics analysis coupled with fracture toughness measurements of the steel, and possibly with non-destructive testing of the joints. This assessment should be carried out using a recognised method such as that detailed in the British Standard BS 7910 [4].

The fracture mechanics assessment will evaluate whether the steel can be used in its brittle range for the intended application. The assessment should examine the proposed structural members and connections to determine their suitability and any precautions and non-destructive examinations (NDE) required.

Recommended Design Practice

There are a number of good practices in design and fabrication that can significantly reduce the stress intensities of structural steel members and joints, thereby reducing the requirements for high levels of toughness:

- Designers and fabricators should be aware of the possibility of anisotropy of mechanical properties, (particularly toughness). Designers should ensure that the material properties quoted are applicable to the intended local direction of stress in the structural member. In general, any plates should be cut and fitted so that the maximum tensile stresses are aligned in the rolling direction of the plate. This may not always be practicable, but should be discussed with the fabricator.
- Connection design should consider actual loads at the joint rather than just the loads derived from the idealised structural model. For example, it is common to design beams as being simply supported, which generates the maximum bending stress in the beam in positions away from the supports (and in any splices along the beam), but nil bending stress at the ends where there is a theoretical pin-ended connection. However, most joints are not strictly pin- ended, and therefore experience bending stresses. Thus it is necessary to analyse the connections with an appropriate model to predict all the critical stresses in the member and joint under design.
- All sections and plates should be sawn or flame cut, not guillotined. The flame cut edges should be ground flush to avoid crack initiation
- Welded connections, especially welds in high stress areas, should be avoided wherever possible. InfraBuild sections can be welded satisfactorily if an appropriate welding procedure is adopted. However, due consideration should be given to the fact that welded joints tend to have a lower toughness than the base metal because of metallurgical changes in the heat affected zone, and stress concentration effects at weld toes, weld defects, and at the corners and edges of welded connections and stiffeners. The effect of this reduced toughness is accentuated at low temperatures. Also, the design standards for welded joints require an allowance for residual stress, usually equal to the base metal or weld metal yield stress unless the weld is stress-relieved. The use of a higher yield stress steel requires a higher residual stress to be used. Increasing the strength of the base material will not necessarily result in an acceptable design, unless the material has a compensating increase in toughness.
- All welds in connections on the tension flanges of beams and columns in bending must be assessed for fracture during design, particularly any welds across the flange. Cracks initiating in welds attached to tension members have the potential to propagate into the tension members. This has been observed in a number of structural failures which have initiated at attachments and incidental welds, rather than in the structural members themselves.
- The following situations should be avoided wherever possible or else, careful consideration should be taken of potential problems:
  a) Welded fin connections without reinforcement at the tension edge.
  b) Joints, especially welded joints, that cannot be fully accessed for inspection
  c) Welds in, and particularly across, the tension flanges of beams and columns in bending.
  d) Fillet welds in tension or bending, unless they can be shown to be full penetration. Any gaps in the penetration of the welds behave as internal flaws in the weld, thus reducing the allowable stresses in the weld. The flange-web welds for long welded beams and columns serve principally to stabilise the web against the flanges and to transmit shear loads to the flanges, so are primarily in vertical compression and in longitudinal tension or compression, so do not usually fall into this category.
- Joints that cannot be fully NDE inspected should be avoided. Where the structure is to contain welds, the fracture assessment will define the maximum allowable size of imperfections in critical welds that will not be detrimental to the performance of the structure. The imperfection size will therefore be based on either workmanship imperfection limits, such as detailed in Section 6 of AS/NZS 1554.1 and AS/NZS 1554.5, or the maximum size of imperfection that can reasonably be missed by NDE in the finished joint or structure, whichever is the larger. This requirement differs from the fracture assessment of clause 6.7 of AS/NZS 1554.1 in which the actual size of the detected defect is used to assess its affect on the integrity of the structure.
- If welds are to be used, then the designer should specify that all weld procedures, and changes to procedures outside the normal range of essential variables as per Table 4.11(A) & (B) of AS/NZS 1554.1, must be qualified. The weld metal and critical heat affected zone (CHAZ) are to be shown to have adequate toughness and to be free of critical defects. The designer should specify inspection and testing requirements for the welds, in consultation with the weld consumable supplier or InfraBuild, as appropriate. All

welds should at least be inspected visually, and all critical welds subjected to more detailed NDE inspection.

- The equivalent defect behaviour of boltholes can be minimised by optimising the sizing, placement and spacing of the bolts and by drilling the holes rather than punching. Boltholes should not be reamed or enlarged as this may lead to crack initiation. As bolted connections do not contain residual stresses, they are generally able to tolerate considerably larger effective defects than welds.
- The bolts for connections should be tested for fracture toughness at the design temperature and the bolt pattern evaluated by fracture toughness methods.
- In general, where fracture mechanics considerations are limiting the capacity of a joint or structural member, well designed fully bolted joints tend to be a more suitable solution than welded joints. Bolted joints may also be more economical than welded joints that require a high quality welding procedure and NDE.

Examples of alternatives to welded joints are:

a) Fully bolted joints. For example, use bracketed and bolted connections to columns etc., and bolted angle cleats in place of welded web side plate connections. Refer to Figure 1.

b) Use a curved roof rather than a pitched roof. In a pitched roof a welded/bolted connection in the rafter is required at the apex. This connection can be avoided or moved off the apex in a curved roof, by roll curving the rafter from a single member. Refer to Figure 2.

c) Appropriately designed purlins bolted directly to the rafters without using welded purlin cleats Refer to figure 2. The welds for the cleats generate residual stresses and local stress raisers in the rafters.

Types of fracture toughness tests and properties

There are several types of fracture toughness tests that can be carried out on steels, yielding information that can be used by different design procedures to assess a given design and service condition. In general, the more precise and useful the information, the more expensive the test. The fracture properties of welds are specific to the welding processes and parameters, so weld qualifications must usually be carried out for the particular situations under consideration. Also, welds are considerably more difficult to test than parent sections, because of the necessity to locate the tested volume within a specific region of the weld or heat affected zone.

Charpy and Izod Impact Tests

The Charpy and Izod impact tests measure the energy absorbed by a standard specimen when it is broken by an impacting hammer. These tests are by far the quickest and cheapest fracture tests. The Charpy test is often performed as a routine production test for certain grades of steel; particularly those made to a standard that requires guaranteed minimum toughness at specific temperatures. Typical costs are in the order of tens of dollars per specimen, and a minimum of three specimens per determination. The Charpy test yields information in the form of a Charpy impact energy (Joules) at the temperature of the test, and can also provide a measure of the ductility of the material and type of fracture under the test conditions. When the Charpy test is carried out on ferritic steels over a suitable range of temperatures, the energy values and the type of fracture indicate the change in the steel's behaviour from tough (ductile) to brittle as the temperature decreases. Based on this, it is normal to define a 'transition temperature', at which the material's properties are about midway between its tough and brittle values.

Table 10.4.1 of AS 4100 is based on the given steel, at the given thickness, having a minimum Charpy energy of 27 Joules at the minimum permitted temperature. Engineering experience has indicated that this energy ensures sufficient ductility to avoid brittle failure in service. However, the Charpy energy itself is not suitable as a property on which to base a quantitative fracture mechanics assessment. Although there are correlations between Charpy energy and fracture toughness available, the more general ones (eg. as given in BS 7910 [4]) tend to give very conservative low fracture toughness values, which in turn lead to high design penalties. Such conversions are mainly useful for initial screening assessments. For major projects it is probably more economic to perform full fracture mechanics tests and use the data to generate more efficient designs.

Pellini Nil-Ductility Temperature (Pellini NDT) test

This test measures the temperature below which a crack will propagate across a plate, rather than be arrested within the plate. As such it is a measure of the temperature at which a material becomes brittle. A design method, based on a simplified form of fracture mechanics, is available which uses the Pellini NDT to determine modes of failure, and critical flaw sizes and loads over a wide range of temperatures.

To perform the test a specific weld is used to generate a notch on a test plate which is then cooled to the required temperature and struck by a falling weight. The weld cracks, and the crack either extends into and across the plate or does not. The temperature is then iterated until the maximum temperature for crack propagation is determined.

The Pellini NDT test typically uses 5 or 6 specimens at a cost of $200 to $300 per specimen.

Fracture mechanics tests: K_{IC}, COD, J_{IC}

These tests measure the fracture toughness of the material, ie. its ability to resist fracture and tearing, at the temperature and loading rate of the test. They are analogous to a material's tensile strength, ductility, and strain energy to failure. For these tests a fatigue crack is worked into a specimen of standard geometry, and the specimen is then loaded until the crack propagates or begins to tear. The loads and displacements of various parts of the specimen are monitored and recorded through the test. The fracture toughness is then calculated from the record. The tests themselves are expensive, in the order of hundreds to a few thousands dollars per specimen, most of which is spent in machining the specimen and preparing it for testing. With appropriate instru-mentation and design of the test, all three parameters (KIC, COD, and JIC) can be tested on the same specimen at the same time, much as Young's Modulus, yield and tensile strengths, ductility, and strain energy can be determined during the same tensile test. The final form in which the fracture toughness is given depends on the behaviour of the material: KIC can only be quoted for tests giving very brittle behaviour. The form of the fracture indicates to what extent the mode of failure of the material is ductile or brittle.

References

[1] Standards Australia AS 4100 - 1998, Steel structures.

[2] Standards Australia AS/NZS 1554 Part 1, Structural steel welding - Welding of steel structures.

[3] Standards Australia AS/NZS 1554 Part 5, Structural steel welding - Welding of steel structures subject to high levels of fatigue loading.

[4] British Standards BS 7910:1999 Guide on methods for assessing the acceptability of flaws in metallic structures.

**1 This design note is based largely upon BHP Steel - Technical Note No. 4 Steel structures for low temperature applications written by David O'Brien and Anthony Ng in Oct 1998.*