Appendix N

Steel Construction Guidance for the Prevention of Brittle Failure

TECHNICAL SAFETY BC

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Commentary on Resistance to Brittle Fracture and Material Toughness from European and North American Steel Construction Standards

The fracture that occurred on the GEE Gondola hanger was a combination of brittle, and fatigue failure. The current adopted code in British Columbia, CSA Z98—14 (the Code) requires the resistance to brittle fracture be considered. However, it is not specific as to how that should be accomplished and leaves it to industry to determine. The objective of this requirement is to prevent a crack from initiating, and propagating to failure without being detected and responded to by owners.

Although the Code does not provide much guidance as it relates to the requirement to consider resistance to brittle fracture, other documentation available to designers provides an interpretation of how this should be considered and incorporated into designs. It is important to note that the manuals referenced below were issued post-construction of the GEE Gondola and it is unclear what guidance was available at the time. In addition, they are typically applicable to structural applications such as buildings and bridges. Arguably, the application of resistance to brittle fracture becomes even more important in a passenger ropeway situation where dynamic loading, and cold temperatures are expected design conditions.

North American Guidance for Toughness

In North America, similar standards and guidance exist when it comes to structural steel construction, for applications such as bridges. The American Institute of Steel Construction (AISC) also discusses resistance to brittle fracture in the Steel Construction Manual, 14th edition. The avoidance of brittle fracture relates to combinations of stress, temperature, strain rate, and geometrical discontinuities (such as notches). It states, "The exact combination of these conditions and other factors that will cause brittle fracture cannot be readily calculated." However, it provides some guidance on factors that increase the risk of brittle fracture, including:

1. Increased Strain Rate – Gravity loads, wind loads, and seismic loads have essentially similar strain rates. Impact loads . . . have increased strain rates, which tend to increase the possibility of brittle fracture."
2. Strain Aging: Cold working of steel and the strain aging that normally results generally increases the likelihood of brittle fracture, usually due to a reduction in ductility and notch toughness.
3. Low Temperature Service: While steel yield strength , tensile strength, modulus of elasticity, and fatigue strength increase as temperature decreases, ductility and toughness decrease.

The AISC has additional guidance when it comes to bending of structural steel tubing. It states that, where ductility and toughness are critical to structural performance, the effects of bending on the material properties should be considered and fabrication needs to be controlled for the structure to perform as intended. Structural members subject to “high strain levels during bending and unfavourable loading, fabrication, or service conditions may require special considerations. . . Ductile performance is dependent on many variables including virgin material properties, level of cold work, service temperature, nature of loading (static, blast, impact, cyclic), level of working stress, level of redundancy, consequences of failure, fabrication quality, and geometry of details (stress concentrations).” It also indicates the further consequences of hot dip galvanizing on cold bent structural members. It states “For cold-worked members that are subsequently heated in the range of 250 deg F to 850 deg F, strain aging is accelerated. Temperatures in this range can be caused by . . . hot dip galvanizing. The manual goes on to indicate that the negative effects can be virtually eliminated by proper post-bending heat-treatment.

It is clear that the effects of cold bending and galvanizing on structural steels are now a well-researched and understood phenomenon in the materials engineering and steel construction world and should be equally considered and understood in the passenger ropeway industry.

European Guidance for Toughness

European standards reviewed often referenced a toughness requirement of (at minimum) 27J at -20 degree C, which consequently is the value the European counterparts of LPOA also specified at the time of gondola construction. This is likely based off empirical data which stipulates that 27 J is the point at which a mild steel is considered to have transitioned from ductile to brittle behaviour (i.e. it’s mid way through the upper to lower shelf transition in the material toughness curve (see figure 1 below).

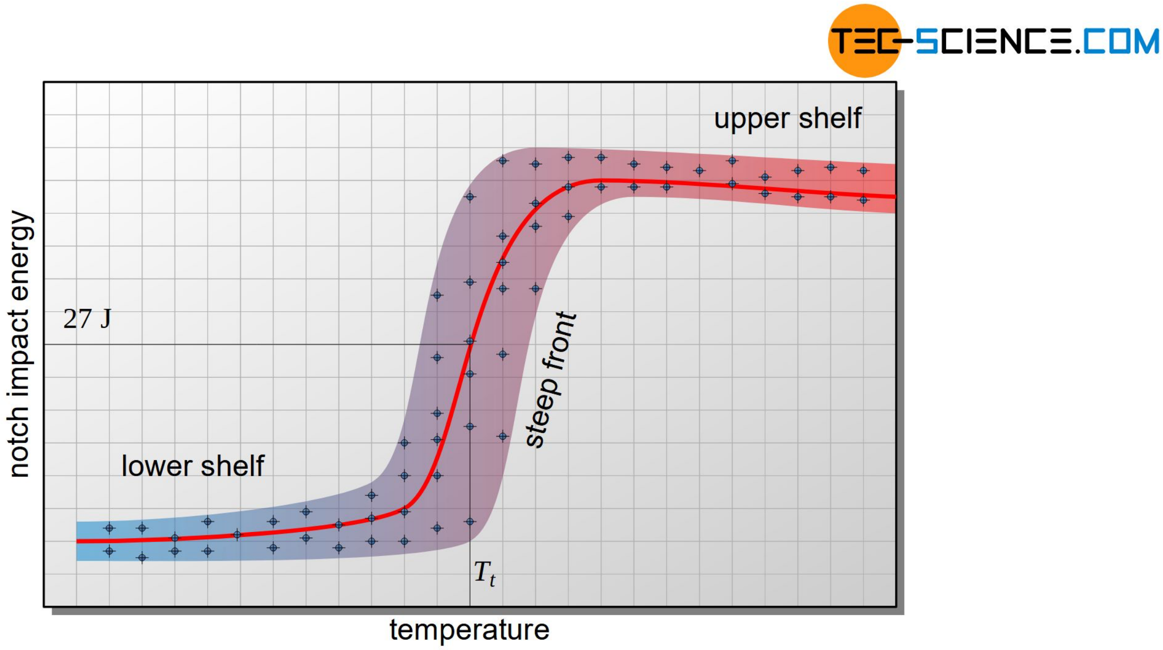

Figure 1 - Notch Toughness as a function of temperature, typical shape for mild steels. Source: tec-science.com (December, 2025)

Design Considerations in European Guidance

EN 1993 is a comprehensive European code used for the design of steel structures and buildings. A joint report prepared by the European commission provides additional commentary on material toughness as a design consideration. It was issued in 2008, after the manufacture of the GEE Gondola.

In discussing material selection, it states that “The selection method for fracture toughness has been developed on the basis of safety assumptions which include the presence of initial cracks (e.g. from fabrication) that may have been undetected during inspections and may grow in service from fatigue.” This is because the ability for a crack to grow is directly related to the fracture toughness properties. Importantly, the determination of whether a material is fit for purpose incorporates two important factors, that loading should be static without an excessively high strain rate, and that cold forming of the material does not result in a significant reduction in material toughness (it specifies <2%). It further states that to “secure ductile behaviour” the designer must specify a material where the material properties are in the upper-shelf region of the temperature toughness diagram (pg. 24).”

The EN 1993 commentary also discusses the concept of damage tolerance which is directly applicable to this incident. It states that service life of a piece of equipment is based on a sequence of safe service periods that are divided by inspections (both regular or “operational” and more in-depth or “main”). It states “The concept of damage tolerance is a feature of structural robustness as it ensures that no failure can occur without pre-warning by very large and visible cracks It also justifies the efficiency of inspections in that it ensures that the occurrence of such large and visible cracks is possible and that those cracks are detectable before a failure will happen.” See figure 2 below.

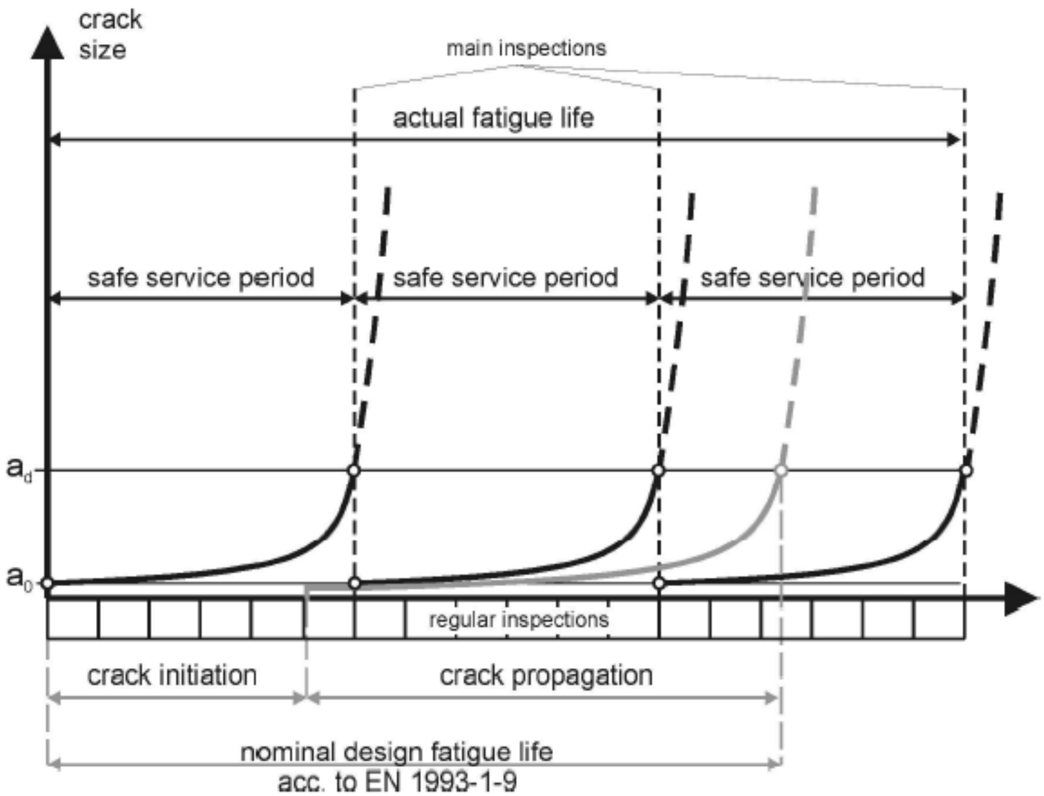

Figure 1 - Graphical representation of the concept of "damage tolerance" as outlined in the EN-1993 commentary. Inspection intervals are commensurate to crack propagation and fatigue life.

It is important to note that that the ability for a material to withstand cracking without complete failure is critical to safety, as it provides multiple opportunities for inspection to catch the crack prior to an incident. This is relevant since inspections cannot be considered 100% reliable in all cases. Although the crack was likely “detectable” in this case during a main inspection, the low material toughness properties would have reduced the necessary critical crack length for a complete failure, shortening the window of opportunity for identifying and responding to the crack.