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Material and workmanship requirements for modern codes of practice

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Abstract. Current codes of practice do not exist in isolation, and rules that have been developed assume certain material properties and minimum workmanship in fabrication and erection. These are either in separate documents or different parts of the code. This paper explains the main requirements for materials and workmanship and how they can be related to design and construction in general. The use of very high strength steels is also considered and the measures that may be needed to allow their use with modern codes are also presented.

Key words: design codes; background standards; materials and workmanship; high strength steels.

1. Introduction

The purpose of codes of practice is to provide design guidance to enable structural engineers to produce acceptable structures. The design strength from the codified rules will depend on the geometry and material properties of the structures as well as defects and inaccuracies in the materials and the dimensions. It is accepted that it is not possible to allow for every possible combination of properties, and the purpose of the codes is to give rules that lead to a low probability of failure. Gulvanessian *et al.* (2002) explain that the usual probability of failure over a 50 year life is 7.2×10^{-5}. The codified rules assume certain values for material strengths etc. and variations in values. Background standards are used to ensure that the assumptions are valid.

Of course the background standards referenced by the codes rely themselves on additional standards. The major European material standard BS EN 10025 (1993) references 40 other standards, including BS EN 10002-1 (2001) and BS EN 10045-1 (1990) on tensile tests and Charpy impact tests respectively. These testing standards themselves refer to a further six and two standards respectively. In the USA, the particular standard for a steel grade, e.g. A992 (2003), refers to A6 (2003) for general requirements while A370 (2003) for testing. The latter two standards refer to approximately 14 and 19 other documents respectively.

It is not just the rules in the codes that are important. An acceptable design can be compromised by inadequate workmanship. In addition to careful design in accordance with the relevant codes, appropriate execution and quality management measures are necessary to achieve the required

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reliability. This is specifically mentioned in BS EN 1990 (2002).

The basic principles of structural engineering are universal, and the codes of practice exist to guide structural engineers in applying those principles to produce acceptable structures. In many cases, judgements are made in producing these codes, and they will therefore reflect the background, concerns and needs of local market and regulations. In contrast to this, steel production is a global industry and mills will usually supply to many markets. Although the producers will usually supply to a range of national material standards, it is advantageous for designers to be able to have some flexibility in the standards, and hence, increase the possible number of suppliers.

Material and workmanship standards are also very important in the use of new materials. Steels with yield strengths up to 460 MPa have been covered by many codes for a significant time. The use of higher steel grades, although limited, may need to be covered in the future. These materials are usually quenched and tempered, and may not conform totally to existing standards. Their use with a particular code would therefore necessitate listing of the basic requirements together with possible restrictions for use of this material.

Codes of practice for design are becoming very comprehensive and are applied to more situations in more details. However, they do not cover every situation and they must not be followed blindly. Similar limitations apply to material standards. In most common design cases, the material standards will not be consulted, but it is important that the designer understands the relevant implict restrictions. The following quotations are from the AISC Specification and British Standard, BS 5950.

> "The intention is to provide design criteria for routine use and not to provide specific criteria for infrequently encountered problems, which occur over the full range of structural design."

> "It has been assumed…that the execution of its provisions is entrusted to appropriately qualified and experienced people."

Many potential problems occur at details, and the steelwork contractor will have a significant influence on the methods and procedures needed to mitigate and avoid problems. In these areas, cooperation between the steelwork contractor and the designer is essential. In some cases, although the designer may recognise the possibility of problems, the solution will rely on the expertise of the steelwork contractor.

2. Basic material requirements

The basic stress-strain diagram (Fig. 1) defines yield and ultimate tensile strengths, as well as ductility. Conventional design has been concerned with the first of these, but the whole shape of the diagram is important. Increasingly when modelling actual performance of structures, the post-yielding behaviour of the steel has to be taken into account, and that is an area where there is a need for more agreement on appropriate curves. As well as the three properties mentioned above, impact resistance, chemical composition and the method of manufacture must be understood before using a chosen type or grade of steel.

2.1. Variation in strength

Material standards require the test results for the yield strengths to be greater than the nominal material property by an acceptable margin. ASTM A6 states that:

"These testing procedures are not intended to define the upper or the lower limits of tensile

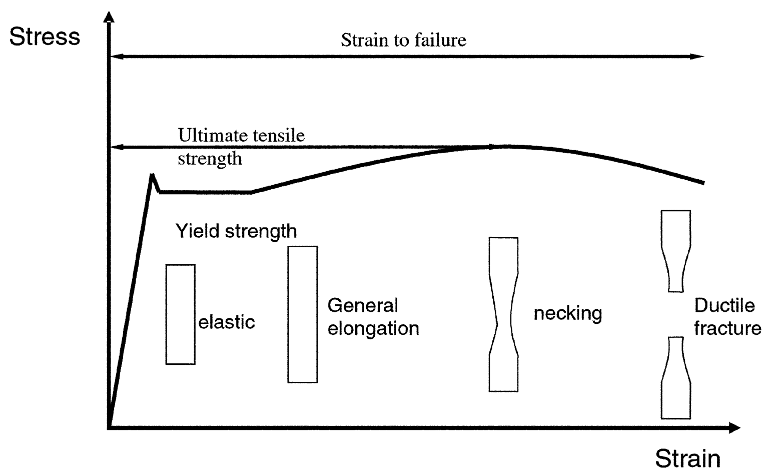

Fig. 1 Stress-strain relationship for steel

properties at all possible test locations.... It is, therefore, incumbent on designers and engineers to use sound engineering judgement when using tension test results shown on mill certificates....The testing procedures have been found to provide materials adequate for normal structural design criteria."

The first point emphasises that the test has only been done as part of the material production. The third point gives some qualitative assurance that there is a sufficient margin of safety, and the second reiterates the importance of having a competent person involved this process.

2.2. Ultimate tensile strength

The design strength of an element is usually based on the yield strength, but in certain situations e.g. for bolts, the strength is based on the ultimate tensile strength (UTS). The UTS is important when considering local effects. For example, for sections with bolt holes, the tension stress is locally allowed to exceed the yield strength, and a UTS significantly higher than its yield strength means the holes do not effect the capacity of the section. In plastic design, the UTS must exceed the yield strength by a sufficient margin to make sure that the plastic hinge extends over a sufficient length to undergo the required rotation. In normal grades of steel, this difference is sufficient, and BS 5950 (2000) has the specific restriction for non-standard grades that plastic design is limited to materials where the UTS is at least 1.2 times the yield strength. ASTM A992 has a similar restriction, but it is expressed slightly differently, i.e., the yield strength must be less than 85% of the UTS. Fig. 2 shows a plot for a typical section with a "flat" moment diagram and that a UTS to yield strength ratio of 1.2 gives approximately twice the rotation as one with a ratio of 1.1.

2.3. Elongation to failure and ultimate tensile strain

Elongation to failure and ultimate tensile strain are both measures of ductility, and without ductility, design in steel will be much less efficient. Design is based on a lower bound set of stresses that may be reasonable, but will very rarely be totally accurate, and the design solution relies on ductility of the steel

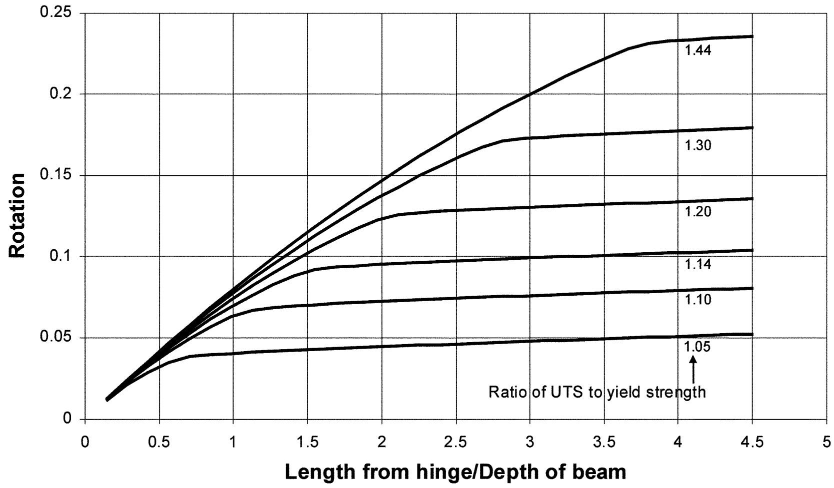

Fig. 2 Rotation adjacent to a plastic hinge

Fig. 3 Eyebar connector

materials to allow for redistribution of internal stresses. This is especially true in connections. An example is that of a pin, and Fig. 3 shows an example of an eyebar used as a pin. Elastic analysis of typical eyebar arrangements will give peak stresses between 3 and 6 times the average stress, depending on the tolerance, it will not be efficient to design for the possible peak elastic stresses. Furthermore, for plastic design, ductility is even more important. Again, BS 5950 (2000) gives minimum values specified for these properties when using the plastic method of design with non-standard materials.

2.4. Impact strength

Brittle fracture occurs without warning and steel materials must be selected to have sufficient impact strengths in order to avoid this phenomenon. Fig. 4 shows a difference between the fracture planes

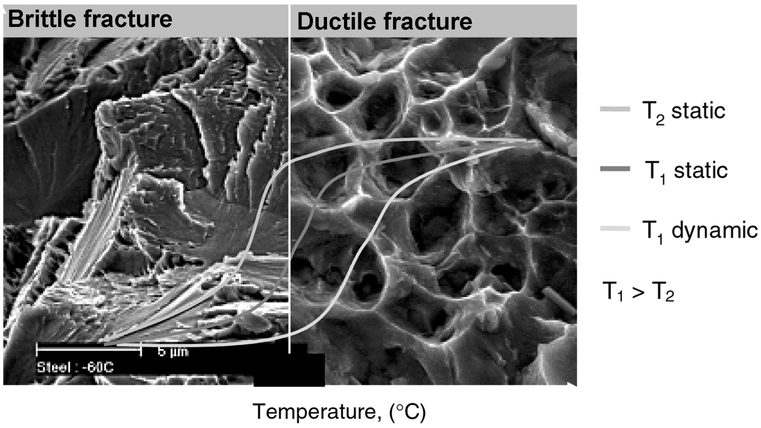

Fig. 4 Brittle and ductile failure surfaces

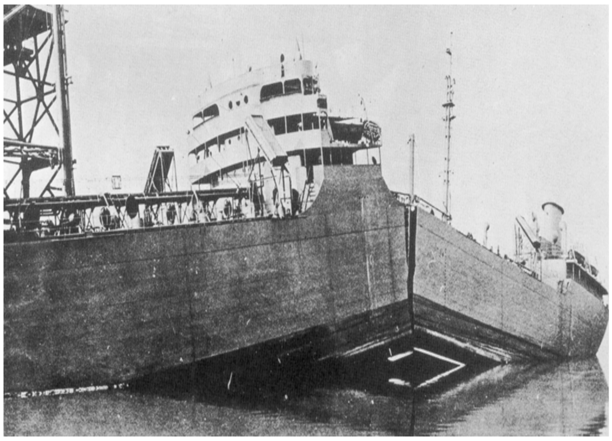

Fig. 5 Liberty Ship with cracked hull

typical of brittle fracture, and the many cup and cones that characterise a more ductile failure. Fig. 5 shows an image of Liberty Ship from the 1940s which was one of the first major examples of brittle fracture. High strain rates increased the risk of brittle fracture, and this phenomena was found in some of the welded details after the Northridge earthquake in the USA and the Kobe earthquake in Japan. The basic level of impact strength required will depend on the minimum service temperature, and the thickness and the grade of steel. Both the connection detail and the stress level will modify the basic requirement. Although it is vital to avoid brittle fracture, specific impact strengths are not required in all codes of practice, nor are they provided as a matter of course by some material standards. The justification of this approach is the lack of problems on the use of carbon steel grades to date.

2.5. Chemical composition

The properties of steel materials are heavily influenced by their chemical composition. Table 1 shows the maximum values of properties for three steels of similar strengths. Although the maximum quantities of the main components are similar, the different standards describe different constituents.

Table 1 Maximum quantities of various elements for certain common steel grades

Grade	C	Mn	Si	P	S	N	V	Co	Cu	Ni	Cr	Mo	Nb	Ti
S355JR	0.24	1.6	0.55	0.045	0.045	0.009								
A992	0.23	0.5 to 1.5	0.4	0.035	0.045	0.015	0.11	0.05	0.6	0.45	0.35	0.15		
Q390B	0.2	1	0.55	0.04	0.04		0.02			0.7	0.3		0.015	0.02

Note: All quantities are in %.

These maximum values are not indicative of typical compositions, for example, the carbon content for A992 steel is typically 0.05 to 0.1% which is very much less than the 0.23 figure in the table. As expected, the weldability of a steel material is affected by its chemical composition, and the usual measure is the Carbon Equivalent Value (CEV). The CEV is a weighted average, and one of the most used formulas for its evaluation is from the International Institute of Welding which is given as follows:

$$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

Despite the importance of this property, it is sometimes not required to be provided by some material standards, and this is justified by experience, based on the assumption that welding will be performed by qualified welders using relevant standard details and procedures.

2.6. Method of manufacture

If the properties of the steel materials are due to heat treatment e.g. for a quenched and tempered steel, they can be affected by welding and also will react differently to high temperatures in a fire. Similarly, a cast material can have different properties to a rolled product. Substitution on the basis of similar design strengths should not be permitted without full consideration on all relevant material properties. The grades given in material standards permit all the above properties to be specified simply and clearly. These material standards refer to other standards, particularly for test methods and procedures.

3. Workmanship requirements

Workmanship requirements for modern codes can either be incorporated into codes of practice, in separate standards or in industry specifications. They will cover preparation, assembly and erection of various parts of a structure. Preparation by cutting, drilling, punching, curving etc. must be performed within tolerance, and must not adversely affect the material properties, e.g. hardness. Assembly by bolting must use the correct combinations of bolt, nuts and washers, and must lead to the correct bolt pretension. Assembly by welding relies on suitably qualified people working to appropriate procedures, and is governed by separate sets of quality control standards. Finally, erection must be safe and produce a structure within erection tolerances.

Tolerances are defined in the workmanship requirements but usually only apply to relatively standard structures. Also in some cases, the main concern is that the tolerance of a structure is compatible with the design assumptions in the design code, and they do not imply suitability for following trades. For many structures, it is often necessary to use project specific tolerances. The major requirement is for a clear communication of the aims by the designer, and also for these to be addressed by the contractor. The joint in the 30 St. Mary Axe shown in Fig. 8 is a good example of this requirement. As the accuracy of the end plate connection was crucial to the fit-up of the complete frame, considerable care was taken by the designer and the contractor concerning the detail to ensure uninterrupted steel erection on site.

As well as the workmanship requirements, most sets of standards specify quality control systems. These can cover traceability of parts as well as measurements to see whether any defects are acceptable.

3.1. Dimensions

Background standards give the dimensions of standard sections, and therefore, allow the designer to quickly specify the section that is required, as well as taking advantage of design guides and data written particularly for standard sections. The background standards also specify the tolerance on dimensions and section shapes, which are important when considering the possible ranges in design strengths. Different sets of standards may be interpreted in slightly different ways. For example, the ASTM standard such as A500 (2003) give dimensions of tubular sections but the wall thickness to be used in design is 0.93 times the nominal thickness, whereas for tubular sections to BS EN 10210 (1997) and BS EN10219 (1997), the design thickness is the nominal thickness.

3.2. Defects and inaccuracies

Workmanship must be such that the level of defects and inaccuracies does not invalidate the design assumptions. Workmanship rules are usually given in a combination of specifications and background standards. The tolerances in section shapes mentioned above are part of the inaccuracies that have to be considered in design codes. Other inaccuracies are tolerances in members (bow, twist etc.) and in the overall dimensions of a structure, e.g. out-of-verticality. Defects can also occur in the basic materials or in welds, and maximum permissible sizes are usually specified which are compatible with design codes. Defects do not have to be geometric, for example inappropriate cutting or incorrect welding can lead to high values of hardness in the steel material, and render it more susceptible to brittle failure.

4. Calibration of design codes

As mentioned above, codes assume certain variations in the design values, and partial safety factors (or resistance factors) will then give an acceptably low probability of failure for these variations. Background standards do not usually specify the variation in the values of design properties, and are based on minimum values. The permissible variation is usually based on established practice from manufacturers. For example, Sedlacek *et al.* (1999) explain how the variation in material properties and dimensions of typical sections produced by major manufacturers were used to estimate suitable partial material factors for Eurocode 3.

5. Recent developments on material specification under global steel supply

5.1. Normal steels

Normal grades of steel, i.e., up to 460 N/mm^2, are produced to many standards and it should be possible to accept steels produced to more than one set of material standards for use with a design code.

A set of standards that can be considered are Chinese, European, American and Australian standards, provided the properties of the steel materials as given in the particular standards are compatible with the assumptions in the design code. As well as a consideration of the particular standards, reassurance can be found by examining the design codes of practice written for particular sets of material standards. If the design codes are similar, it is likely to have similar assumptions about material properties. Steels produced to the sets of material standards mentioned above should probably be acceptable, though certain anomalies may exist, and additional information may be required. For example, it is not normal practice to specify impact strengths for steel to ASTM standards, but these are necessary for many design codes.

When a steel material is produced to a material standard, the designer has a reasonable basis for making decisions about acceptability. However, in a number of cases, the designer has been faced with the use of steel that needs to be classified by testing, and it has been shown above that a simple strength test is not sufficient. One of the main problems in this situation is to assess the possible variability in the properties over the range of elements. In these cases, testing regimes should be established to reflect the particular circumstances. An alternative in these situations is to make conservative assumptions about the properties of the steel materials, for example, AS 4100 (1998) has clauses for such "unidentified steel".

5.2. Ultra high strength steels

When using a steel material with a yield strength greater than 460 N/mm^2, the situation is more complicated. Some of this material is produced to particular manufacturer's specifications rather than to established material standards. The experience in the use of this material is limited, and the use of a higher material safety factor may need to be considered. Many of the basic requirements, such as ductility, will be similar as normal steels. In some cases, the ratio of UTS to yield strength may limit the applicability of the steel material. One of the main difficulties with this steel material is the requirement for welding which, although possible, must take account of the different relevant welding procedures. Using techniques applicable to normal steels can lead to problems. Figs 6 and 7 show examples of weld metal hydrogen cracking and hydrogen cracking in a welded joint in ultra high strength steel respectively.

Fig. 6 Weld metal hydrogen cracking of ultra high strength steel

Fig. 7 Hydrogen cracking of ultra high strength steel

Fig. 8 A node connection in the 30 St Mary Axe Building

6. Additional concerns and non-typical problems

Standards are technical documents and cannot include all the possible requirements that may be placed on the designer. An example is the increasing need for safety issues to be taken into consideration in design. These can influence the choice of materials and construction processes. Obviously, the steelwork contractor will have a significant influence on these issues.

Standards also only reflect the consensus of past experience. New or infrequent problems are not covered, but need to be appreciated. Examples of these are centreline segregation and liquid metal assisted cracking (LMAC). Figs. 9 and 10 show a detail and an elevation of the cracking of a plate due to centreline segregation. Centreline segregation is a material deficiency that exists within the centre of

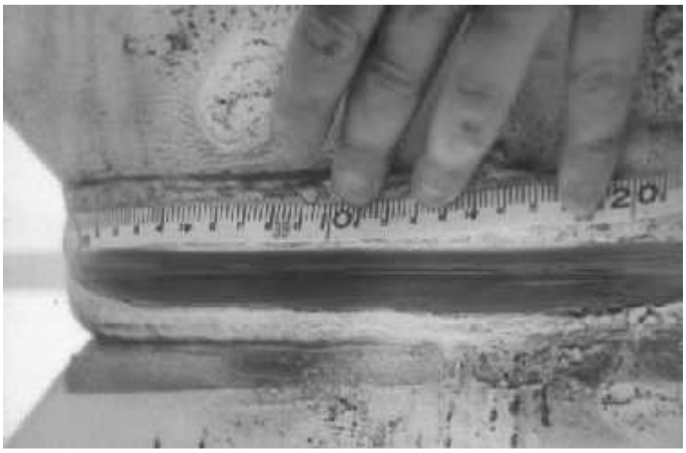

Fig. 9 Elevation on plate with cracking due to centreline segregation

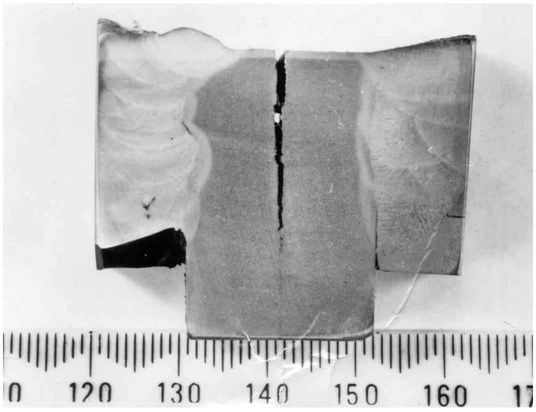

Fig. 10 Detail of cracking due to centreline segregation

plate (concast) products and some sections. It can lead to local reductions in toughness and weldability that can cause cracking in tee-butt and cruciform weld configurations. The use of good welding practice and detailing may be sufficient to avoid this phenomenon, but there is not yet a consensus on the most practical approach.

Figs. 11 and 12 show cracks in a gusset plate due to LMAC where the galvanizing process induces cracks in susceptible details. The cracking occurs during the galvanizing process, but unfortunately, it may be masked by the zinc, and not become apparent until after the structure has been erected. Levels of hardness, residual stress, steel grade and thermal stress induced by galvanizing are factors that influence the occurrence of this phenomenon, but again there is not yet a consensus on the most practical way of avoiding it.

Both centreline segregation and LMAC are significantly influenced by workmanship. Successful implementation of measures to avoid these problems will be assisted by cooperation between the designer and the steelwork contractor.

Fig. 11 Cracking in gusset due to LMAC

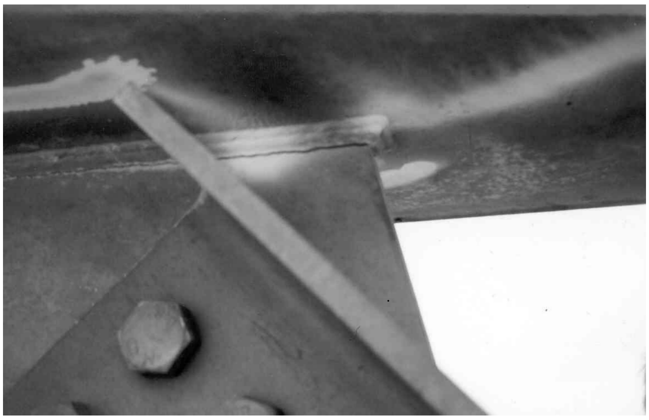

Fig. 12 Cracking in gusset due to LMAC

7. Conclusions

This paper shows how modern design codes rely on many background standards. The areas covered by these standards are explained together with some of the main reasons for particular requirements. In certain areas, e.g. impact strength and welding, certain approaches are based on the satisfactory performance of normal details. Some additional concerns and non-typical problems are noted. Although the designer needs to be aware of the areas where the generally accepted standards may need to be modified, the steelwork contractor has significant expertise in these areas. The most efficient way to avoid difficulties is by cooperation between all parties at the earliest possible stage.

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