QUALITY MATTERS – MATERIAL REQUIREMENTS IN EUROCODE (EN 1993) IN VIEW OF COMPONENT SAFETY

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Abstract

Building steel structures in the European area includes not only technical aspects but also requirements on compliance with legal rules set up by the European Union for all member states. This is similar to the case of pressure vessels where the directive, PED 97/23/EC, gives the framework for delivery of vessels into Europe. The CE-sign demonstrates compliance with this procedure to the customer. Technical standards like Eurocode 3 (EN 1993) or EN 13445:2009 for pressure vessels can be used to achieve direct compliance with such European Directives.

Material requirements play an important role during the design process of welded steel structures. Generally the design is orientated depending on the function and the safety of the construction under both normal operation and extreme conditions. Maximum stresses, operation temperatures and loading type (static, dynamic or cyclic) on the loading side (S) lead to the selection of materials with sufficient properties on the resistance side (R). The calculation is performed as a limit state calculation which in the easiest way may be expressed by the equation:

$$S < R$$

This paper highlights how the limit conditions of maximum load-bearing capacity, fatigue and especially avoidance of brittle fracture are addressed in Eurocode 3 and in EN 13445. The application of modern fracture mechanics methods is taken as a specific example to demonstrate how, by means of engineering science it was and is possible to quantify the toughness requirements, while simplifying the use of such methods. Further, it will be outlined why and how within the new design system, quality in fabrication plays a very important role.

Finally, it shall become clear that a model which is transferable for all kinds of welded constructions requiring safe, economical and sustainable design is available for all interested parties all over the world.

Introduction

Steel is the most important material for industrial applications of all kinds. One could say: “Steel is the backbone of modern technologies.” Though sometimes felt to be an old fashioned material in the public view it is obvious for all engineers dealing with steel that at least during the past 40 years there has been a huge development step in steel metallurgy and processing. The use of microalloying techniques with niobium and/or other elements in combination with thermomechanical controlled deformation processes or quenching and tempering, and secondary metallurgy making steel as clean as possible, has led to modern types of steel for construction purposes with the highest quality level. But is it steel quality alone that matters? The answer is a clear "No" and the reasons shall be explained within this paper.

To do so it is necessary to have a closer look at the working process that leads to an operation-ready welded steel construction and to identify the parameters that influence the working process, as such, and allow the main requirements to be met. These can be formulated in the most general way as follows:

i. Safety against catastrophic failure;
ii. Economical erection;
iii. Sustainable operation until end of life.

It is worth noting at this stage, that Points i and iii are of highest public interest whereas Point ii is mainly of private (shareholder) interest. That is why in many areas Points i and iii are ruled by governmental directives or laws whereas for Point ii the technical and physical rules of design, fabrication and material properties are sufficient. This often leads to controversy and sometimes can even be an obstacle for application of modern technological developments.

Figure 1 shows the three major factors that must be considered within the working process: Material, Fabrication and Construction. All three have their own technological basics and developments. Typically engineers are working predominantly in one or other of these areas, which could result in a narrowed view with regard to optimum, overall solutions. However, as the bolts in the figure shall show, it is necessary to consider all areas at the same time with respect to their interactions.

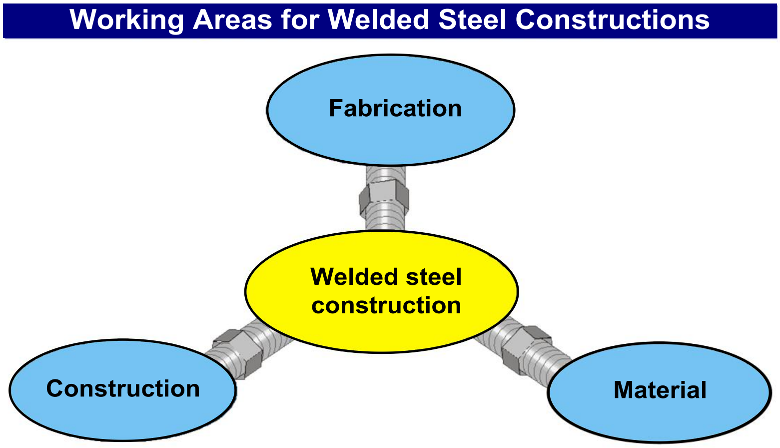

Figure 1. Principal areas governing safe, sustainable and economical design of steel constructions.

A good example of this interaction is welding. To weld successfully one must know how to weld (machine, electrode, power, handcraft, etc.). But in addition you must also know something about the steel (chemistry, heat treatment condition, weldability, strength, etc.). Finally, the designer must know about the difficulties that arise from complicated welding positions or on-site welding with respect to possible degradation of assumed properties. Usually a well-educated and experienced welding engineer knows about all these things, which always makes it advantageous to have a welding engineer involved.

Consequently, it is necessary to develop a set of technical rules which, if followed correctly, guarantee compliance with the above mentioned three major goals. In Europe these technical rules are linked to European Directives. In the case of steel structures the Directive 89/106/EEC is the legal framework to be met and in the case of pressurized components it is PED 97/23/EC. Both formulate the requirements to achieve safety and sustainability. The technical rules accompanying these directives are the EN 19xx (with xx = 90 to 99) series and EN 13445 for pressure vessels, and EN 13480 for piping. One can find similar systems in various other countries outside Europe.

The basis for the material requirements in such technical rules is often not clear and also it is often not known why it is important to achieve compliance with such requirements and why the process must be monitored by third party inspectors. This shall be clarified within this paper on the basis of Eurocode 3 and EN 13445 for pressure vessels as examples.

Limit State Design

The design process is always at the beginning of a new welded steel construction. During design the following limit states must be addressed to find the component geometry and material strength required:

i. Serviceability Limit State (SLS);
ii. Ultimate Limit State (ULS);
iii. Brittle Fracture Avoidance (addition to ULS);
iv. Fatigue Limit (addition to ULS);
v. Corrosion Avoidance.

The Serviceability Limit State (SLS) and Corrosion Avoidance are direct consequences of the functional service of a construction and therefore, govern particularly the economic aspects of a construction like material selection of High Strength Steel, or long life corrosion protection by using stainless steels or zinc coated steels. This part of the design leads to material with a certain minimum yield strength and corrosion resistance as expected from the corrosive environment. More important with respect to safety is the ULS, including Brittle Fracture Avoidance and the Fatigue Limit.

In all these cases, if the described limit was reached during operation, it would be followed by more or less catastrophic failure. Therefore, it is necessary to develop rules that allow a safe behavior even under accidental loading situations (eg. earthquake or sudden drop of temperature or fatigue cracks which had not been seen during inspection).

The basics of a limit state design can be reduced to the formula:

$$S < R$$

with S representing all Loads and other design conditions (including design temperature where this has an effect on stability) and R representing the material Resistance (eg. yield strength, tensile strength and toughness). Both sides of the equation can be filled with appropriate formulas describing the physical behavior of a construction, such as force/area (F/A) = σ for all stresses, σ, on the loading side, or yield strength, as a function of temperature, Re = f(T), for steel on the resistance side.

In addition, it must be considered that there is scatter in the input values for loads and material properties and that the design equations applied have a model uncertainty. Therefore, it is necessary to introduce safety factors on both sides of the equation. In the case of the Loading side in European standards it is good practice to apply partial safety factors Ψ in addition to a general safety factor γ_S. On the Resistance side a general safety factor γ_m is usually applied due to the fact that material values are taken as nominal values from technical standards such as EN 10025. In this context the nominal value means that there is a 95% probability that the real material value is higher than this value. Equation 1 then reads:

$$\Sigma\gamma_s G_K + \psi_1 Q_{K1} + \Sigma\psi_{2,i} Q_{Ki} \leq Re.\gamma_m \qquad (1)$$

with

G = permanent loads
Q = non permanent variable loads
γ = safety factor
Ψ = partial safety factor

All five Limit States are addressed in design codes like Eurocode 3 (EN 1993) or EN 13445 and EN 13480. These codes will shortly be introduced before being discussed in more detail which impacts on material and fabrication requirements resulting from Limit State Design.

European Standards in Area of Public Regulation

As pointed out before it is important to know that in Europe the public intention is that health and safety of people and protection of the environment are of paramount importance, which forces the governments to publish directives or laws which control such areas. Two major technical areas which are government-ruled in Europe are:

- Directive 89/106/EEC for steel structures;
- PED 97/23/EC for pressurized components.

To put any steel construction into place and operation it is necessary to produce it in such a way that compliance with the technical requirements can be achieved, along with compliance with the regulatory rules. The responsibility to achieve compliance lies in the hands of the producer of the steel structure including the selection of a competent third party for monitoring the process. These competent third parties must also be approved by the rules set up in the European Directives. This opens the market to all market participants if they are able to comply with the rules.

The technical standards which are ideally applied are the harmonized European Standards. This means EN 1993 for steel structures with EN 1090 for fabrication and EN 13445 for pressure vessels and EN 13480 for piping.

Using harmonized standards results in the pre-assumption of conformity which means less need for monitoring through third parties. A simple example is the steel selection according to EN 10025 in relation to EN 1993 or from EN 10028 (pressure vessel steels) in relation to EN 13445. If, alternatively, steel with a non-European (eg. ASME) designation should be applied, the constructor would be forced by the law to produce an individual (Particular) Material Appraisal (PMA after EN 764-4) to demonstrate compliance with the regulations of the Directive. The effort to satisfy such a process depends on the decision of the competent body. If a standard is harmonized, this can be seen from the Annex ZA, which is attached to all harmonized European standards. For a steel producer, for instance, this means that he can deliver according to EN standards, if he is approved by a competent body for his full production system, to guarantee the minimum properties. Another example in this context concerns welding of steel. If weldments are performed it is necessary to have approved welding personnel and approved welding procedures, but it is not necessary to produce the weldments in Europe.

Figure 2 provides an overview of Eurocode 3 (EN 1993) Series [1].

Overview Eurocode 3 (EN 1993)

No.	Generic Rules	No.	
1.1	Bar Structures	2	Bridges
1.2	Fire	3	Masts, Towers
1.3	Cold Formed Sec.	4	Silos, Large Storage Tanks, Pipes
1.4	Stainless Steel	5	Sheet Piling, Piles
1.5	Plate Buckling	6	Crane Runways
1.6	Shells		
1.7	Plates in Bending		
1.8	Connections		
1.9	Fatigue		
1.10	Brittle Fracture		
1.11	Cables		
1.12	Extension S700		

Figure 2. Ultimate Limit State design overview from Eurocode 3.

Effect of Limit State Design on Material Requirements

<u>Ultimate Limit State (ULS)</u>

Figure 3 shows the load deflection (R-v-δ) curve of a beam. The curve shows linear elastic behavior at first and deviates into a slowly decreasing slope with strain hardening due to plastic deformation capacity. Though the curve shows that plastic deformation continues after the maximum engineering stress, R, for design and construction purposes it is correct to assume the maximum as the Ultimate Limit State. Upon reaching the Ultimate Limit State in a real construction no further load can be borne even though plastic deformation could continue. For construction steels the described behavior can generally be assumed to be valid as long as brittle fracture conditions can be excluded (see the section on Brittle Fracture Avoidance). This means that the material requirements to be defined must somehow reflect the plastic behavior. In Eurocode 3 (EN 1993) this leads to the following requirements for all strength levels allowed:

- Fracture Elongation $A_5 \geq 14\%$;
- Yield to Tensile ratio $Y/T \leq 0.9$.

These simple figures reflect the simplified engineering understanding of utilizing the strain hardening capacity of steel. They are not toughness oriented, because sufficient toughness is assumed for this type of deformation oriented safety margin. Note that in case of earthquake loadings the construction must sustain even more plastic deformation with up to ten plastic cycles. Here special requirements are set up going beyond those for normal areas.

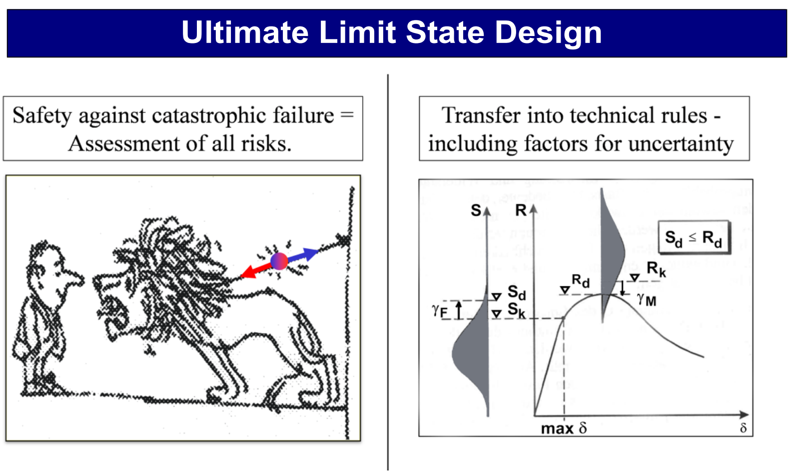

Figure 3. Ultimate Limit State design: loads (S), strength (R), deformation (δ) and safety margins (γ).

Another important point is highlighted in Figure 3. Both the applied Loads (S) and the material properties (R) are parameters subject to statistical scatter. This means that for the design the minimum material properties are used whereas the material deliverer must guarantee for his customer that these minimum levels are achieved. Normally this is done with material certificates. In European Design the certificates are published in accordance with EN 10204 and provide measured values for strength, ductility and toughness in relation to a Technical Delivery Standard of the steel employed. Typical European material standards which are in compliance with the design rules are:

- EN 10025 (parts 1 to 6) for EN 1993 (Eurocode 3);
- EN 10028 (parts 1 to 6) for EN 13445 (unfired pressure vessels);
- EN 10216 (parts 1 to 4) for EN 13480 (piping);
- EN 10217 (parts 1 to 4) for EN 13480 (piping).

Both in Eurocode 3 and in the case of pressurised components (EN 13445 and EN 13480) it is necessary that the material producer is qualified by a Quality Management System according to EN rules or that a 3.2 certificate (to EN 10204) is delivered. This means that testing must be performed by a competent body approved by the regulations of the respective European Directive.

For the steel-fabricator this means that, in the as-delivered state of material supplied according to an EN standard, he can assume compliance with the rules. However, in case of any doubt it remains at all stages his responsibility for the welded construction he intends to produce. In consequence, it is sometimes recommended to counter check the material. Here the most important point to be made is the fact that: *Quality matters*. Buying material from an incompetent producer bears a high risk of failing the compliance check and a high risk of producing unsafe constructions. Checking the company, the material or both, before welding can help avoid high costs of repair or replacement at a late stage.

Another important discussion concerns the limitation of the Y/T ratio to certain maximum values. From Figure 4 it can be seen that the Y/T ratio approaches one with increasing strength. However, it can also be shown that such steels still have a true plastic deformation capacity, that the Y/T ratio is not a sufficient indicator of toughness and that the above described effect is exaggerated under simple, uniaxial tensile loading. The required provision of uniaxial properties therefore, punishes the higher strength steels by not considering the true loading conditions. Therefore, it can be stated that safe design, as described above, can be achieved with high strength steels if material selection, design and fabrication are carried out properly. This brings us again back to the earlier statement: *Quality matters*.

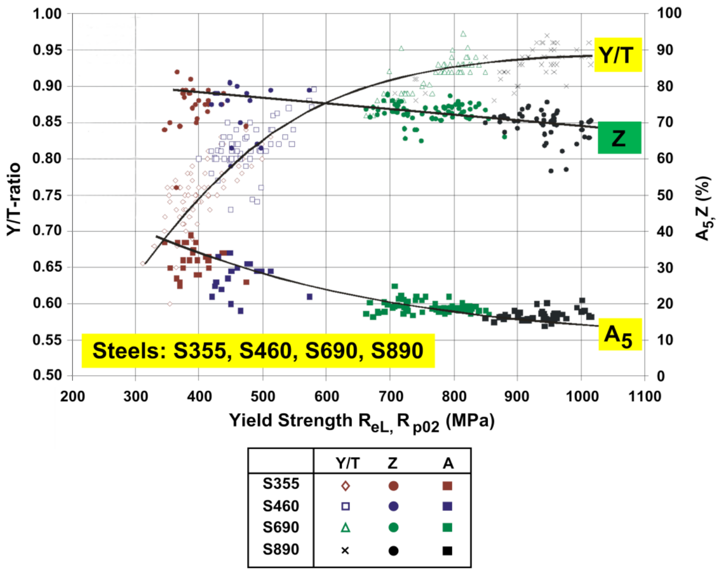

Figure 4. Dependence of Y/T, fracture elongation A and reduction of area Z on strength level of structural steels [2].

Brittle Fracture Avoidance

In the case of avoidance of brittle fracture, an important physical aspect of steel deformation behavior of body-centred cubic steels (ferritic steels) is addressed. From Charpy tests, well known to all engineers, we experience a loss of load-bearing capacity of the specimen expressed as a decrease of fracture energy, when going down to below room temperature. The reason for the loss of load-bearing capacity cannot be found on the mechanical scale, because the stress triaxiality ahead of the crack is only dependent on the geometry which is the same for all specimens, however it can be explained from material behavior in terms of plastic deformation ahead of the notch tip on the microscopic scale. With reduced temperature the thermally activated deformation on the micro scale becomes more and more limited. The stress triaxiality ahead of the notch can not be reduced by plastic deformation anymore. Remember here that the latter was the pre-condition for reaching the ULS (upper shelf in the Charpy test). At a certain point the first principal stress becomes so high that it reaches that required for cleavage fracture: The fracture is initiating-stress controlled which on a macroscopic level is identified as Brittle Fracture. Figure 5 shows the fracture stress schematic over the temperature axis.

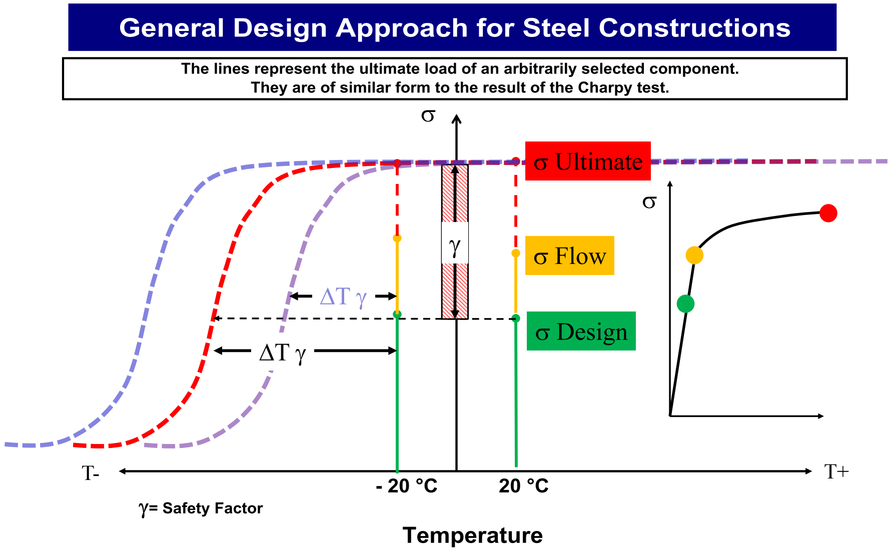

Figure 5. Schematic transition behavior of ferritic steels with respect to maximum load-bearing capacity along the temperature axis for construction steels [3].

The transition temperature at which the load-bearing capacity drops (Figure 5) in a real construction as opposed to the Charpy test must be known to formulate boundary conditions that allow the avoidance of brittle fracture. In other words it is necessary to assess all effects that influence the transition temperature to formulate the material requirements. These influences are:

- Maximum design stress at lowest design temperature;
- Lowest design temperature;
- Fabrications that alter initially assumed material properties;
- Imperfections that result from fabrication process and cannot be avoided and are overseen during initial or subsequent inspections;
- Component geometry especially with respect to thickness.

The material property which now is of relevance is no more the global ductility as defined before but the toughness. Toughness is defined as the capability of a material to reduce stress triaxiality by local plastic deformation. In consequence, we get a lower transition temperature for materials with higher toughness and we get higher toughness for higher quality materials produced with the modern steel and microalloying technologies mentioned in the introduction. This again stresses the main message: *Quality matters*.

The derivation of toughness requirements appropriate to build safe and economical constructions is often under discussion. Many rules that are applied today result from experience with steels in the 1960s and 1970s. A more sophisticated way to derive toughness requirements was developed during the 1990s using knowledge of fracture mechanics which was derived in the course of nuclear engineering in the 1960s and 1970s in Europe, the USA and Japan. The method was simplified with respect to avoiding expensive fracture toughness testing by employing the so called Master Curve Concept (MCC) in combination with the Failure Assessment Diagram FAD (Figure 6).

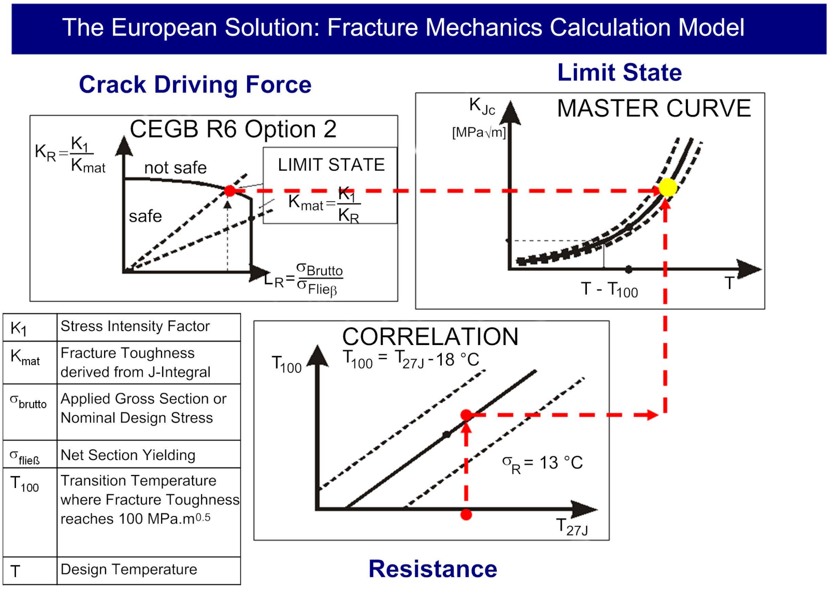

Figure 6. FAD plus Master Curve Concept: The European solution to apply fracture mechanics in a cost effective way [4].

Now it became possible to derive the toughness requirement based on the realistic assumption that imperfections in welded constructions may grow under cyclic loading and become critical (the triaxiality ahead of the crack causes the shift of the transition temperature for brittle behavior to higher temperatures) with respect to the ULS state or brittle fracture.

With the help of this new system that was verified with numerous European Steel Research Projects [3,5,6,7] it was possible to quantify toughness requirements and relate the result with the Charpy transition temperature T_{27J} or T_{40J} as given in many technical delivery standards (like the aforementioned EN 10025 and EN 10028). At the end the designer needs little effort to derive the right combination of steel strength, thickness and toughness from a standard table. The advantages for future developments result from the analytical calculation model which can be adopted for new or individual challenges. For example, it was possible to extend the thickness limitation in EN 13445 from 110 mm to 200 mm by pre-normative research (Joint Industry project, sponsored by Industry and conducted by IWT Projects Ltd.) [8].

It is important to note with respect to the aim of this paper that all assumptions made for the model do not only consider the quality of the material, but also the quality of fabrication steps and proper design according to the given rules. Good fabrication quality means that qualified welders perform all the weldments and that ideally a welding engineer is in charge of all aspects of the fabrication processes. He has an important role to mediate between the requirements on safety and economy whilst applying the related design rules without compromise. No mixture of standards is allowed because every standard has its own safety assumptions consistently through all parts. The steel user who applies European Standards for steel holds an important technological role with many possibilities of achieving cost savings.

In consequence, it is easy to achieve appropriate toughness requirements when using the proposed fracture mechanics based methods adapted to a system of safety assumptions. Those methods and assumptions apply over all areas, as given in Figure 1, which are followed by the producer and designers. Or in other words: *Quality matters*.

Fatigue Limit Design

Fatigue is the most often identified reason, after corrosion, for failures of steel construction. A proper Fatigue Design is therefore of great importance. Many studies have been performed to derive design rules which follow the Limit State Design idea. However, both on the resistance and on the loading sides of equation 1 one can find high levels of uncertainty.

The most common procedure used for welded constructions is the Nominal Stress Concept. In the case of the Eurocode the designer can use part EN 1993-1-9 to relate typical constructional elements with tolerable maximum fatigue stresses $\Delta\sigma$. The limit lines as shown in Figure 7 were derived from several tests performed during the last decades, not only in Europe, but all over the world. They are lower bound lines with a 97.5% probability.

On the loading side, where possibly variable loads occur within the lifetime, the designer must calculate the distribution of loads and apply Miner's Rule for cumulative damage to derive safe behavior throughout the lifetime of the structure. This is common practice and is, therefore, applied in a similar way for pressure vessels, ships and windmills. A good overview is given within the IIW document XIII-2151-07/XV-1254-07.

In the case of cyclic loaded structures, it is most important to achieve the required quality level. This means that the construction must avoid critical geometries and stiffness jumps, or uses cast nodes with smooth radii instead of welded nodes and make the design in such a way that welding can be performed under good working conditions or weldments are not placed in highly stressed zones. A good design engineer knows this and helps the fabricators with his knowledge. In consequence: *Quality matters* in the design stage, especially for cyclic loaded constructions.

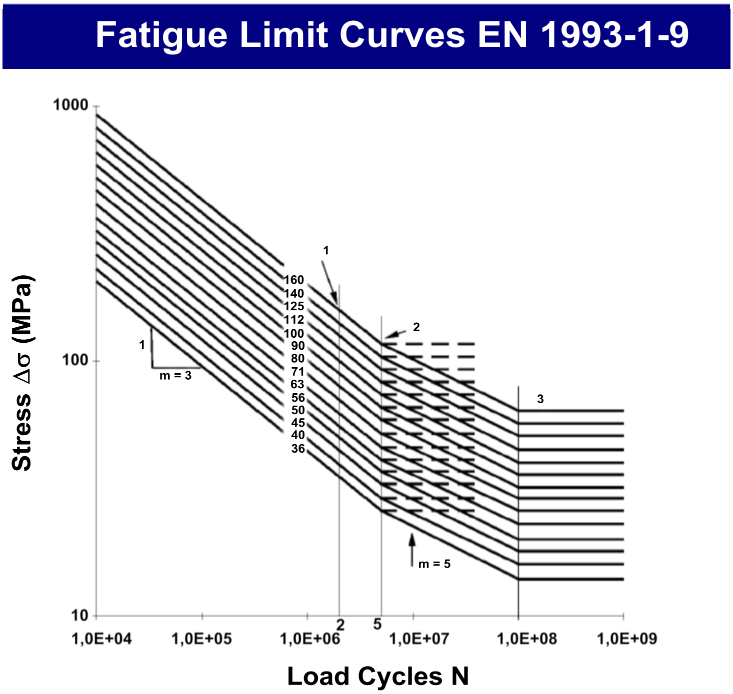

Figure 7. Fatigue design in EN 1993-1-9.

Much more important here is good workmanship for welding. The better the welding personnel are qualified, the better the fatigue resistance of the structure. As a principle of quality work in the case of large and complicated constructions, a welding engineer should always be involved. The next point is about detection of possible imperfections by NDT (non-destructive testing). NDT should be applied carefully.

Nevertheless it must be accepted that overlooked imperfections may lead to unexpected slow crack growth and increase the danger of total failure, ductile or brittle. This has already been considered in the toughness requirements of Eurocode 3 (EN 1993) by assuming that the crack growth is subcritical (safe) within the period between two inspections. This means that a crack which started just before one inspection and is again overlooked can grow to such a size that it is still sub-critical until the next inspection. This demonstrates how the normal fatigue design can be combined with the toughness requirement for cyclic loaded constructions.

Conclusions

Building new steel constructions like bridges, high-rise buildings, pressure vessels and piping in public regulated areas in Europe is ruled by directives published by the European Commission. Such regulations shall help society to avoid situations where catastrophic failure of the construction could lead to injury or loss of life, or have unacceptable impact on the environment. Such rules are not technical. The technical rules to build the constructions are given in European Standards like EN 1993 for steel structures and EN 13445 for pressure vessels or EN 13480 for piping systems. These standards are so called harmonized standards which means that applying the standards leads to achievement of conformity (CE-sign). In the case of materials and welding, which need to be considered in the initial design process, related European standards are available which are also harmonized. The application of this system of standards follows the idea of Limit State Design in combination with partial safety factors and the assumption of minimum material properties as given in the harmonized material standards.

It has been demonstrated that applying this system of standards for material requirements makes construction safer and more economic if quality measures are implemented at all levels. In detail it was demonstrated that:

1. Modern quality steels such as microalloyed grades make constructions safer and welding more economic.

2. Recognition of material properties from material certificates beyond the nominal design values avoids expensive surprises during fabrication or operation.

3. Well-educated welding personnel and individual responsibility by a welding engineer make the weldments much safer and reduces possible failure and repair.

4. Proper design helps avoid failure from fatigue and complicated welding situations which could lead to failure during welding or in operation.

5. Application of the latest technologies for welded construction, by their implementation into standards, is possible by means of Joint Industry projects.

6. The owner of a steel construction can earn more money from the intended operation if no failure occurs during operation and that only the application of technical standards together with quality measures can guarantee this.

7. Quality usually costs more money in the beginning but saves money over the life time.

Overall, in conclusion, one can truly say: *QUALITY MATTERS*.

It is fully consistent with respect to maximizing profit, protecting the world we are living in and satisfying people who like to perform their work at their best and be paid fairly for doing so.

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