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REVIEW OF STRENGTH – TOUGHNESS RELATIONSHIP FOR VARIOUS STRUCTURAL STEELS GRADES

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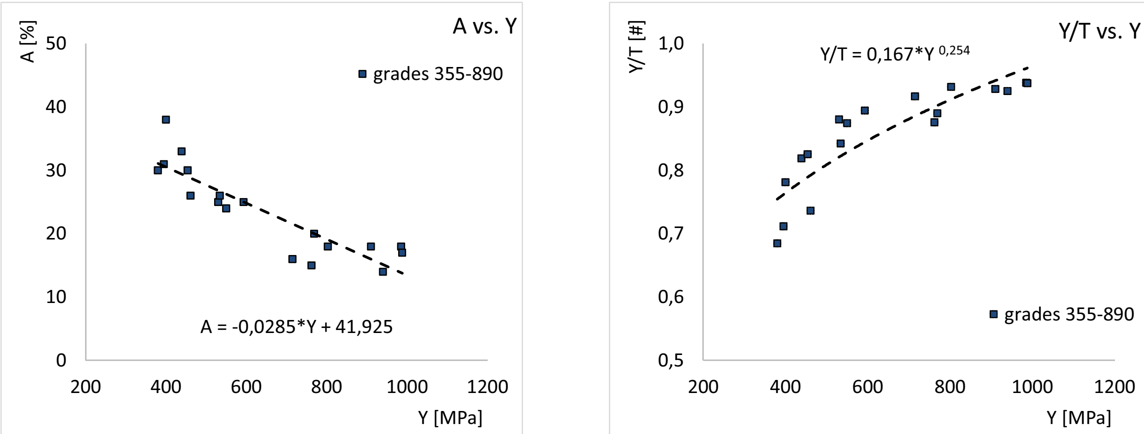
ABSTRACT
Avoidance of brittle fracture for steel structures is one of the major design concerns. This implies that base materials must possess sufficient level of toughness and an appropriate brittle-to-ductile transition temperature. Also, necessity to use of steel structures and products on higher stress levels, by use of high-strength steels – a mean for provision of lighter and more efficient structures is an increasing demand. Thus engineers must be aware of one combined influence of strength and toughness for selected base materials. Paper presents review of actual engineer's friendly concepts of strength - toughness relationship. However, two most influencing variables, thickness and design temperature, also must be considered, when dealing with strength & toughness levels.
Various experimental results, both from own research and other found in reference literature, for base and weld metals of several strength level structural steel's are compared to existing relationship terms.
Keywords: strength, toughness, relationship, structural steels

1. PREFACE
A structural steel is well known and unique material with good combination of high strength and high toughness. While high strength allows provision of light steel structure, a high toughness provide good resistance to crack initiation and growth. Thus, when last two are properly combined within design, structural steel should provide desirable yielding before fracture for extreme loading condition. However, when stress states are high or complex, e.g. when plain strain condition exist on larger thickness; as well as if minimum design temperature is mistakenly underestimated regarding transition temperature; a structural steel may behave in dangerously fast brittle manner. Therefore, it is important to consider joint influence of thickness and minimum design temperature on toughness behavior. Moreover, even not present as demanding influential parameter within engineer's friendly product standards; load strain rate may also significantly influence both strength and toughness.
Such concept is well known in many demanding welded products design standards or codes, either for pipelines, pressure vessels, storage tanks, or even for general steel structures. Thus, design engineer must be aware of general strength – toughness relationship; and never to underestimate the importance of toughness as design variable. However, both strength and toughness are mainly dependent on chemical composition and processing route of a selected steel; e.g. delivery condition. Such data may be easily fund in both steel manufacturers specifications and/or corresponding delivery standards; but rather precisely within steel mill certificates.

This paper deals with two toughness parameters: e.g. impact toughness KV [J] and fracture toughness K_{Ic} or K_{mat} [$MPam^{0,5}$]; and major strength property: e.g. yield stress Y (R_{eH} or $R_{p0,2}$) [MPa]. Major differences between KV and K_{mat} is in the fact that KV is obtained from notched specimen, while K_{mat} beside notch possess also initial crack. Therefore, as a real structures or products may contain various micro or macro cracks (or imperfections), concept of K_{mat} defined by a Fracture Mechanics (such as within SINTAP/FITNET procedures), is of particular importance.

2. EXISTING CONCEPTS

It is generally well known, that increase of strength of structural steel leads to decrease of elongation after fracture, or ductility A in [%] (Fig. 1a); and increase of Y/T ratio (Fig. 1b), where T is tensile strength in [MPa].



a) Yield stress – Ductility relationship *b) Yield stress – Y/T ratio relationship*

Figure 1. Relationship of strength (yield stress, Y), ductility (A) and Y/T ratio; based on the Tab. 1

Decreased ductility, A, and higher Y/T ratio, decrease capacity of a material to resist crack growth in ductile manner, and thus general toughness, either KV or K_{mat}. Also, high Y/T ratios for structural steel are not allowed within design standards and codes; such as maximum allowed Y/T=0,9 within Eurocode; and therefore very high-strength steels (Y>890 MPa) may not be utilized.

To compare and further evaluate for relationship (terms) of strength (Y), fracture toughness (K_{mat}) and impact toughness (KV); at least the thickness and testing temperature of test samples should be constant. Thus for the purpose of this paper, available experimental data consider always test results at room temperature, e.g. 20°C; and sample's thickness, either of base or weld metal, in the range from 15 to 30mm; and always for K_{mat} corrected for thickness of 25mm (K_{mat-25}). Relationship term for corrected K_{mat-25}, based on K_{mat} for thickness B in [mm] is provided in SINTAP procedure [1]:

$$\frac{K_{mat} - 20}{K_{mat-25} - 20} = \left(\frac{25}{B}\right)^{0,25} \quad \ldots(1)$$

Beside there is a various relationship terms of K_{mat} and KV, particularly for groups of structural steels; the following generalized terms specify lower bound, or rather conservative values, as per [1]:

$$K_{mat-25} = 12 \cdot KV^{0,5} \quad \ldots(2) \quad \text{and} \quad \left(\frac{K_{mat}}{Y}\right)^2 = 0,52 \cdot \left(\frac{KV}{Y} - 0,02\right) \quad \ldots(3)$$

The term (3) is not always an appropriate for lower bounds [1]; and with a bit different coefficients is known as the "Barsom-Rolfe" term or correlation [2].

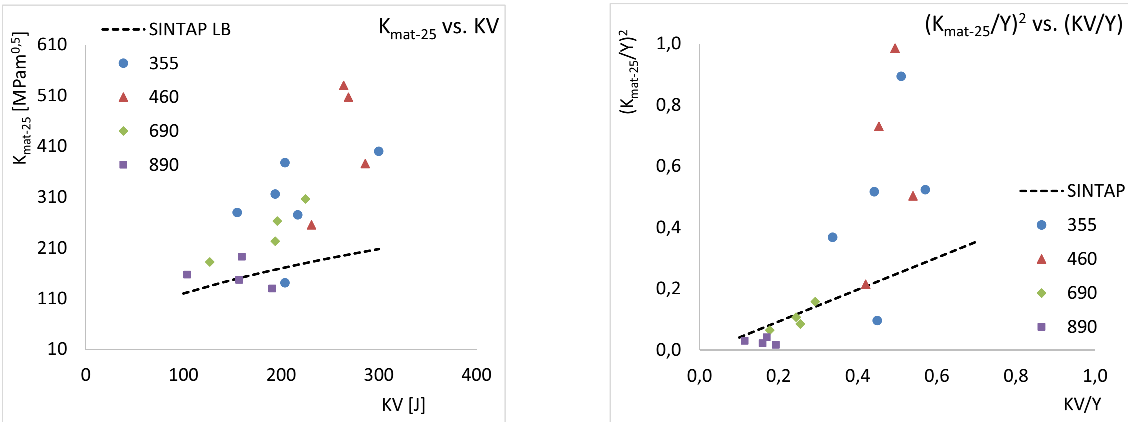
3. EVALUATION OF AVAIABLE EXPERIMENTAL DATA

For the evaluation of existing concepts, the various experimental data are used, both from other researches [3,4], as well as some own [5]. Selected steel grades were from nominal Y=355 MPa, 460, 690 and 890 MPa, and various delivery conditions (N, M and Q) (Tab. 1).

Table 1. Range of evaluated structural steel grades [3,4,5]

Steel grades / Nominal Y	Delivery conditions	Thickness range [mm]	Y [MPa]	T [MPa]	Y/T	A [%]	K_{mat-25} [$MPam^{0,5}$]	KV [J]
355	N, M	15-25	380-461	512-626	0,685-0,825	26-33	141-400	155-300
460	M, Q	15-25	530-593	602-663	0,842-0,894	24-26	255-530	196-286
690	Q	15-30	715-803	780-870	0,876-0,932	15-20	182-306	127-225
890	Q	15-25	910-988	980-1054	0,925-0,938	14-18	130-192	104-191
N-Normalized, M-Thermomechanical treatment, Q-Quenched and Tempered.								

Based on the range of data, as generally shown in Tab. 1, relationships are evaluated for K_{mat-25} versus KV as shown on Fig. 2a, and $(K_{mat-25}/Y)^2$ versus (KV/Y) as shown on Fig. 2b. Bounds per SINTAP terms (2) and (3), are also shown respectively.



a) K_{mat-25} *versus KV* *b)* $(K_{mat-25}/Y)2$ *versus (KV/Y)*

Figure 2. Evaluation of impact toughness, KV, and fracture toughness, K_{mat-25}*, and yield stress, Y.*

Also, relationship K_{mat-25} versus Y is shown on Fig. 3, as well as proposed lower bound relationship term; of course, applicable only for selected structural steel grades range (nominal Y=355-890 MPa).

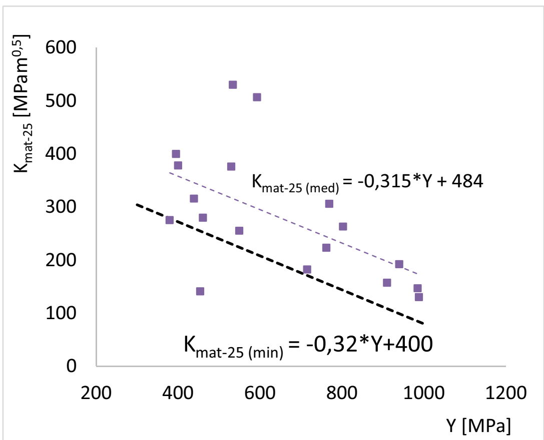


Figure 3. Relationship K_{mat-25} *versus Y, and proposed lower bound r.t.*

Even scattered data show difference ΔK_{mat-25} up to +200 $MPam^{0,5}$ for 460(Q) structural steel grade; the general lower bound relationship term between fracture toughness, K_{mat-25}, and yield stress, Y, could be, as per Fig. 3:

$$K_{mat-25} = -0{,}32 \cdot Y + 400 \quad \ldots(4)$$

This principally show a general trend of fracture toughness decrease while strength of structural steel increase.

Bounds per SINTAP [1], and terms (2) and (3) show good and conservative conformance, particularly for grades 690 and 890.

Obviously, structural steel grades 355 and 460 show quite higher levels of toughness, as per Fig. 2; in comparison to prediction as per SINTAP terms for lower bounds. Of course, this is an expected trend for novel structural steel grades, particularly those thermo-mechanically treated (M).

4. FINAL REMARKS

One of the key inputs for any structural integrity assessment; either for assessment of existing products or during design of new ones; is the fracture toughness, usually determined by an appropriate fracture mechanics-based test. However, in many situations complex and expensive fracture mechanics test are not available; while Charpy impact toughness (for KV) and tensile testing (for, Y, T and A) are rather simplified and more accessible. In these cases it is necessary to use a correlation between impact energy, KV, and fracture toughness, K_{mat}. For sufficient conservatism, a lower bounds are mainly used [1].

However, not all structural steel grades could be sufficiently utilized if lower bounds are considered as per [1], particularly those with medium level of strength and processed by thermomechanical treatment, where really high toughness level may be achieved. In such cases it is better to use available relationship terms in relevant reference literature, based on a research of fracture mechanics parameters for such grades [5,6,7].

While structural steel is rather predicted for utilization and designed for temperature lower than room temperature, e.g. minimum design temperature, MDT, it is important to use toughness values which correspond to MDT.

Secondly, the thickness is also important influential parameter. Actually, increased thickness may lead to so called plain-strain condition and therefore minimum possible toughness levels. This principle is already implemented into various design standards or codes. Therefore, based on nominal toughness level and delivery condition (processing route), for one structural steel grade and selected minimum design temperature, the maximum allowed thickness for utilization are defined.

Finally, the attainment of both strength and toughness is a vital requirement for most structural materials; unfortunately these properties are generally mutually exclusive. On one side, the high strength structural steel allow provision of light and economically beneficial structures and products; while contrary the high strength could not be sufficient for provision of minimum required toughness at predicted or minimum design temperature, MDT.

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