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Meeting technological and social challenges – Sustainable design principles for damage tolerant microstructures

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Abstract – For advanced high strength steels for automotive application, the time between materials development and regular use in cars, trucks and similar vehicles is rather short. In contradiction to this, hot rolled plates made of high strength low alloy steels which have been developed many years ago still do not find application fields in structural steelwork although they offer impressive mechanical properties. In this paper we argue that inadequate design rules in civil and mechanical engineering prevent such modern high strength steels from displaying their lightweight potential. A technological approach to the problem presented in this paper is to apply damage mechanics models together with probabilistic safety concepts for derivation of new improved safety factors. However, a major obstacle in this process is that these new safety factors will have to be included in the design standards. The development of such standards contains both institutional and epistemic obstacles to including alternative safety models. Taking standardization in Europe as an example, the standardization committee is characterized by both national interest representation and attempts to stimulate European integration and competitiveness. At the epistemic level, different understandings of what counts as evidence for material safety may challenge and postpone adoption of new calculative models. Institutionalization and epistemology thus contribute to a framework for standardization that needs to be questioned in order for new approaches to be accepted. Such questioning cannot be done on the basis of developing new calculation models alone, but needs a clear social component of building coalitions around the inclusion of new considerations, for example those related to sustainability.

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The development of high strength steels with remarkable damage tolerance has been fostered for the last three decades, both for ecological and economical reasons. For sheet materials, multiphase steels such as TRIP or DP grades were developed which offer excellent strength and ductility. These advanced high strength steels (AHSS) were mainly used for automotive applications, and since there are no design rules in terms of European or national standards in automotive engineering, these newly developed sheet materials have found their way into application rather quickly (Fig. 1).

For hot rolled steels in thicker gauges, thermo mechanical rolling as well as quench-and-temper processes have been established to achieve an improved profile of mechanical properties in high strength low alloy (HSLA) steels. Obviously, the production of these excellent materials is based on a precise adjustment of microstructural configurations which has been developed based on two simple principles: avoid critical microstructural constituents which are the nucleation sites for any kind of micro crack, and improve the matrix in order to find the best compromise between strength and ductility. The economical relevance of this material development can be deducted from Figure 2, in which the possible cost savings as a result of using high strength sheets has been shown. It can be clearly seen, that the use of high strength sheets yields a considerable amount of economical advantages. Apart

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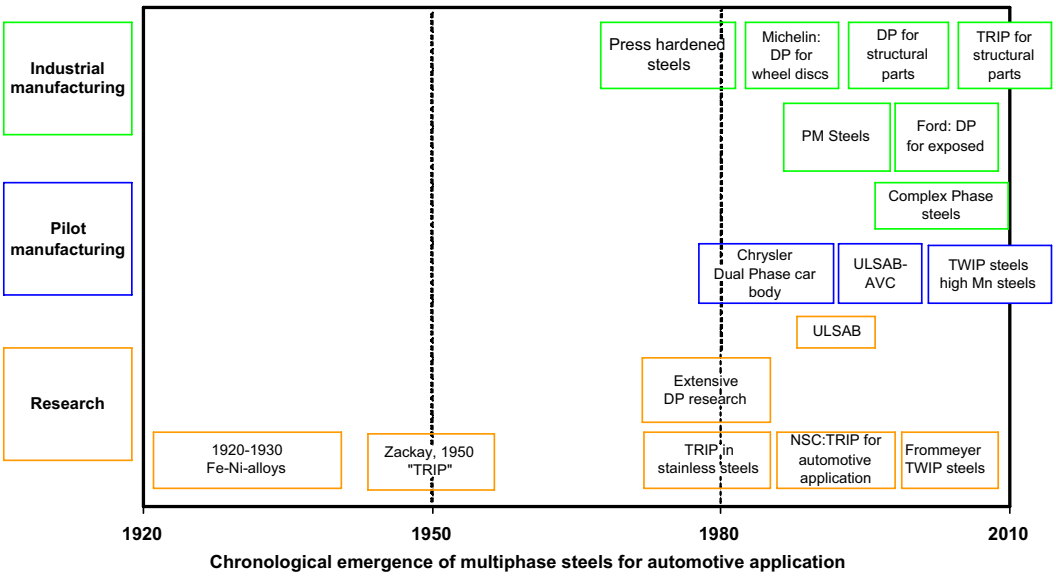
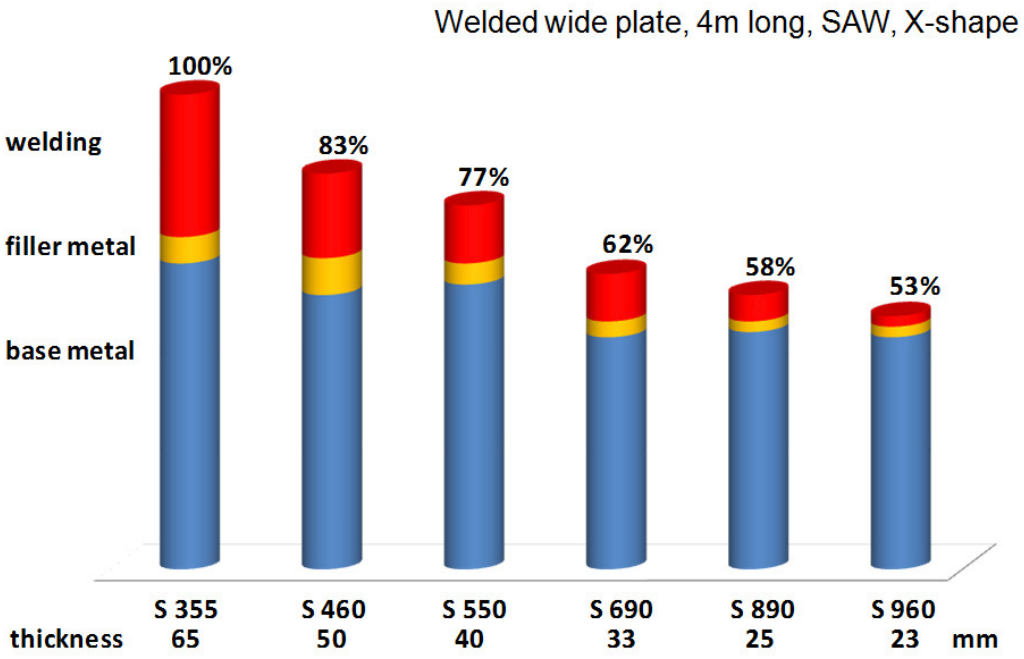


Fig. 1. Development of advanced high strength steels and first application in automobiles.



Source: AG der Dillinger Hüttenwerke

Fig. 2. Economical benefit and lightweight potential from the use of HSLA steel.

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from the efficient use of resources during the production of HSLA steel, it also leads to a considerable cost saving during the joining process because less amount of filler material is needed. Furthermore, there is the possibility of welding without post heat treatment because of the small thickness of the plates. The use of these steels offers hence several advantages:

- from a constructive point of view, it offers potentials for saving weight (light weight construction);
- the economical benefits result especially from the joining process because labor costs and consumption cost can be reduced;
- ecological advantages arise because of the sustainable construction method: reduction of the total energy by decreased consumption of resources and consequently a reduction of the CO_2 output is possible.

However, in contradiction to the AHSS for automotive application, the HSLA steels are not widely used for structures and components in civil and mechanical engineering despite advantages of their use in terms of costs and sustainability. An important obstacle to their use is the difficulty of valuing HSLA steels in the process of standardization for applications. This problem has a technological and a social dimension. In the following, both technical and social aspects are addressed in order to explain the limited acceptance of these modern materials in standard setting.

1 Technical and social obstacles for the use of hsla steels

So far, most steel components are designed according to limit state concepts relying on mechanical properties guaranteed by the steel producer. For the sake of simplicity and economy, the designer mainly relies on the minimum yield strength of the steel which is defined in European standards, e.g. EN 10025 [1] (structural steels), EN 10208 [2] (pipeline steels) and EN 10028 [3] (pressure vessel steels). Hence, so far the limit state for these components is local plastification instead of crack initiation or component instability. Aiming to fully exploit the property profile of modern HSLA steels, it must thus be the aim to include physical sound measures for ductility into the design procedures.

The use of HSLA-Steels is affected by European design standards from civil and mechanical engineering which do not reflect the properties of the steels sufficiently. This is due to the fact that conventional design rules are only extrapolated in the field of high strength materials and this leads to an extremely conservative estimation of the properties of these group of metals. Consequently, these design rules will have to be modified for the future. From a technical point of view, the necessary steps have already been planned [22–24], and in the following paragraphs, the engineering solution approaches will be presented. However, one has to fear that although these engineering solutions will be provided soon, the modification of the design standards will be delayed extensively because of sociological problems of acceptance. Since the applied engineering methods to prove the safety of structures and components made of HSLA steels are more and more dominated by sophisticated modeling approaches from the materials mechanics community, the question what the role of standards in innovation is becomes more complex. Standards are often associated with facilitating exchange of technologies and stimulating innovation, but experiences with the difficulties of setting norms for HSLA steels suggest otherwise. An important social question related to acceptance of new innovations is therefore how standardization works and how it affects innovation. These aspects of standardization will be discussed later in this paper.

2 Finding a solution in the technical dimension

In order to achieve a safe, economical and sustainable use of high strength steels with the aid of the European standards for structural steelwork in civil engineering, the use of the probabilistic safety concepts is suggested. In contrast to deterministic methods,

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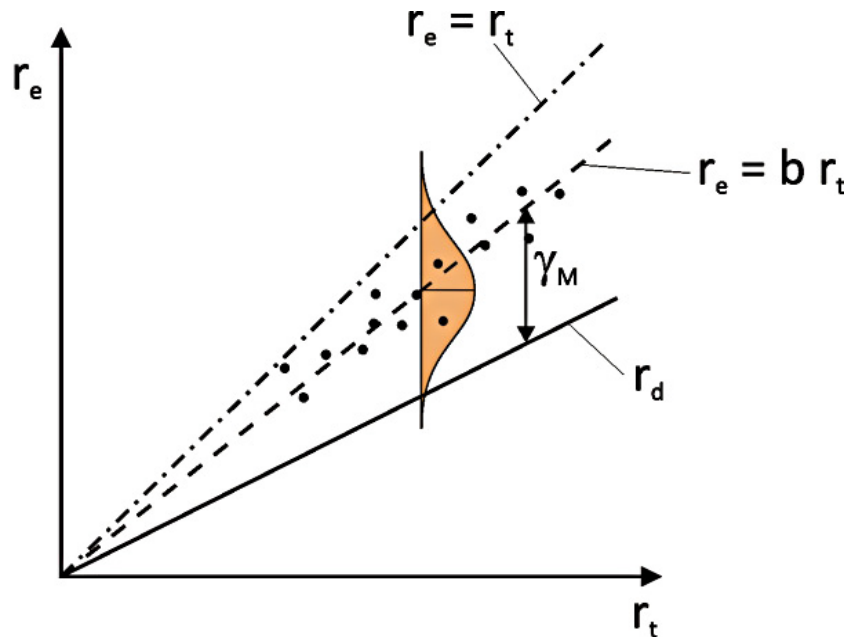


Fig. 3. Determination of safety factors according to probabilistic safety concepts.

the associated safety factors for a desired probability of failure are calculated in a reproductive manner through statistical methods. The rules for deducing the safety factors from the probabilistic concepts can be found in appendix D of EN 1990 [4]. Already in the past, these methods have been applied for the European design rules for civil engineering, but in many cases the material's plastification was considered as limit state. Now, both ductile crack initiation and plastic instability of component shall be taken into consideration. For this purpose, the limit loads r_e provoking one of the two mentioned failure modes have to be gathered in component tests. Afterwards design model predictions are determined as r_t values for cases examined in the experiments with the methods stated in the dimension standards without considering the safety factors. If the r_t values are plotted against the r_e values, the plotted pairs spread around a line through the origin with a slope b. This spread will be described statistically in the next step, in such a way that an associated safety factor can also be deduced eventually through the declaration of an acceptable probability of failure.

The implementation of this method will however be unsuccessful due to lack of sufficient database of component tests which are made from high strength steels. Apart from that, it can be assumed that the economical cost saving through the use of high strength steels can only be achieved on a long term, considering the cost of acquiring the required data from lots of component tests. To that effect, it has been suggested that the experiments on the components should be done through damage mechanics simulation methods. The required damage models will be introduced in the next paragraphs.

The GTN damage model belongs to the group of micromechanical ductile damage models. Gurson [5, 6] analyzed a spherical void in an infinite perfectly-plastic matrix material in order to define a yield potential for a porous plastic material. This yield condition was later modified by Tvergaard and Needleman [7–9]. It can be used to describe isotropic strain hardening and it is expressed as follows:

$$\Phi_{GTN} = \left(\frac{\sigma_v}{\sigma_y}\right)^2 + 2\,q_1\,f^*\cosh\left(\frac{3}{2}\,q_2\,\frac{\sigma_H}{\sigma_y}\right) - \left(1 + q_3\,f^{*2}\right) = 0$$

with:

σ_v: von Mises equivalent stress;
σ_y: matrix material yield stress;
σ_H: hydrostatic stress;

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q_1, q_2, q_3: model parameters to define the shape of the yield surface;
$f*$: effective void volume fraction.

The effective void volume fraction $f*$ is a function of the void volume fraction f, which is the ratio of the total volume of all cavities to the volume of the body. The effective void volume fraction $f*$ was established in order to consider void interaction effects starting at a critical void volume fraction f_C. The function to calculate the effective void volume fraction $f*$ reads:

$$f*(f) = \begin{cases} f; & f \le f_C \\ f_c + \kappa(f - f_C); & f > f_C, \end{cases}$$

with:

$$\kappa = \frac{f_u^* - f_c}{f_f - f_c},$$

f_C: critical void volume fraction;
f_f: void volume fraction at macroscopic failure;
$f_u^* = f*(f_f)$: effective void volume fraction at macroscopic failure.

In this function, the accelerated damage evolution after reaching the critical void volume fraction f_C is described by the scalar value κ. The void volume fraction f is calculated according to a void evolution law. It considers growth of existing voids with the initial volume fraction f_0 as well as nucleation and growth of a second void population. The nucleation of new voids of the volume fraction f_N is assumed to be a strain controlled damage process [10]. The damage evolution law reads [11]:

$$\dot{f} = \dot{f}_{\text{growth}} + \dot{f}_{\text{nucleation}} = (1 - f)\,\dot{\varepsilon}_{kk}^{pl} + \frac{f_N}{S_N\sqrt{2\pi}} \times \exp\left[-\frac{1}{2}\left(\frac{\bar{\varepsilon}^{pl} - \varepsilon_N}{S_N}\right)^2\right]\dot{\bar{\varepsilon}}^{pl}$$

with:

$\dot{\varepsilon}_{kk}^{pl}$: plastic volume dilatation;
f_N: fraction of void nucleating particles;
S_N: standard deviation of strain controlled void nucleation;
$\bar{\varepsilon}^{pl}$: equivalent plastic strain;
ε_N: characteristic strain of void nucleation;
$\dot{\bar{\varepsilon}}^{pl}$ rate of equivalent plastic strain.

The advantage of GTN model is the fact that lots of parameters from the void evolution law can correlate with the microstructural properties. For example, series of experiments have shown that the initial damage can be understood as volume fraction of sufficiently large non metallic inclusions, because primary pores are formed in these inclusions for most steels for applications in civil engineering. A similar argument awakens the assumption that the parameter f_N is equivalent to the volume fraction of carbide precipitation. Due to the fact that other model parameters can be derived from both values with the aid of numerical studies, GTN model can be widely seen as micro structurally motivated. Thus, a possible way of describing the spread of load bearing capacity within a given steel grade depends on the derivation of various GTN parameter sets that reflect the scatter of upper shelf Charpy impact toughness and applying these different sets in full scale simulations of component tests. However, just like most of the other locally formulated micromechanical damage models, the GTN model has a pronounced dependency on the mesh size; this in turn usually requires an extensive sub model simulation, if the ductile failure behavior of large components has to be examined. Consequently, the computing time would be too expensive. An alternative approach would be to consider only marginal sets of GTN parameters which lead to lowest and the highest values of the expected Charpy impact energy within a given steel grade, from which the simplified failure criteria can be derived and finally applied in the numerical component analysis with less computing time. An applicable empirical failure criterion for this approach will be introduced subsequently.

Since ductile failure of steel is a strain-controlled process, the equivalent plastic strain to fracture ε^f is a suitable measure for the ductility of steel. Both experimental studies and theoretical investigations have concluded that hydrostatic pressure exhibits a significant influence on the equivalent plastic strain to fracture ε^f [12–19]. Therefore, in many cases the stress triaxiality η, which is the ratio of the first to the second invariant of the stress tensor, is used as a variable to

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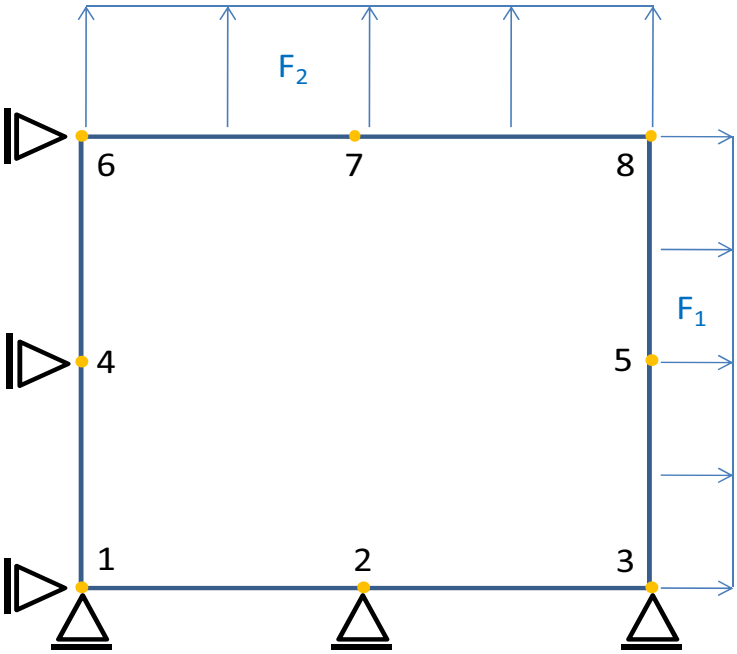


Fig. 4. Cell model to derive the damage curve in GTN simulations.

express the equivalent plastic strain to fracture ε^f.

The equivalent strain to ductile fracture is determined in a combined experimental and numerical approach. The procedure begins with loading of a sample to provoke ductile fracture. In the next step, the local spot where this micro crack appeared is investigated in metallographic investigations, and afterwards the test is simulated in order to evaluate the local stress and strain state for the time step that corresponds to the critical loading situation identified in the experiment. The described procedure has to be repeated for different specimen geometries in order to modify the state of stress and strain which result in the initiation of ductile micro cracks. Most typically, cylindrical notched bars in tension and compression, plane strain tensile samples and shear samples are tested to cover a wide range of stress triaxiality η.

An alternative method to derive a material's damage curve using the GTN model is presented in [20]. The procedure is based on cell model simulations which can be performed with low computational costs. The cell model presented in Figure 4 consists of a quadratic axis-symmetric cell with 8 nodes and reduced integration. During the simulations, the stress triaxiality η is kept constant at η = 0.5, 1, 1.5 and 2 since a constant ratio of loading F_1/F_2 is applied during the whole calculation. For the time step when the maximum equivalent stress is reached, the equivalent plastic strain is extracted from the output file of the simulation. The following chapter presents how these models can be used to prove the safety of components made of HSLA steels. Furthermore, an outlook is given how these findings can contribute to the calculation of improved safety factors by application of probabilistic safety concepts.

3 Application example: pressure vessel steel P500Q

The studies conducted started with a conventional determination of the material's damage curve. For this purpose, several modified fracture mechanics specimen were strained to the point of ductile crack initiation. After these experiments, the location of micro crack formation was determined with aid of metallographic analysis. This is followed by a simulation of the experiments and determination of the equivalent plastic

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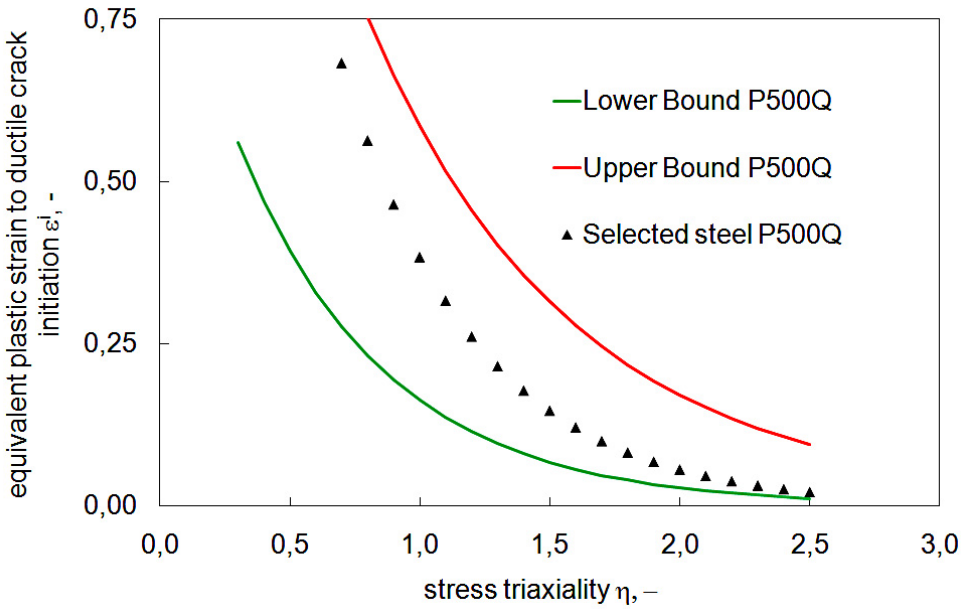


Fig. 5. Upper and lower bound damage curves of steel grade P500Q.

strain values ε^i and the stress triaxiality η at the point of the micro crack formation. Thereafter, the GTN parameters were determined in order to simulate a notch bar impact test it the upper shelf. During this process, the mesh size and the coefficients of friction were specifically adjusted. For the iterative adjustment of both values, the result of an instrumented Charpy test has to be resorted to. Subsequently, this model should be applied in order to determine the iterative adjustment methods for the sets of GTN parameters that leads to the lowest and the highest Charpy impact toughness values for a steel P500Q. These threshold values of the Charpy toughness for a given steel grade were determined with the aid of Master curve concepts and empirical correlations. If highest admissible T_{27J}- temperatures are being implemented, the minimum upper shelf Charpy energy can be calculated. It is also possible to estimate the highest possible Charpy energy through an experienced based guess of the lowest possible T_{27J}-temperature. With this method, it was discovered that the upper shelf Charpy impact toughness for steel P500Q should lie between 60 J and 250 J.

In the next step, the notch bar impact test was simulated with the aim of calculating the minimal and maximal upper shelf Charpy impact toughness of 60 J and 250 J. This was done by applying the optimized model with regards to the mesh size and friction coefficient. Figure 5 shows the upper and lower bound damage curves for steel P500Q determined with cell model calculation, with regards to the method of determining the sets of GTN parameter. It is also shown that the damage curve for the examined steel P500Q lies within this area of dispersal.

To demonstrate the safe capacities of the investigated material (but so far permitted to utilize), a model pressure vessel was designed according to the standard of the design for unfired pressure vessels. The vessel consists of a cylindrical shell with an outer diameter of 3000 mm and spherical bottoms at both ends. The wall thickness for analysis was chosen to 50 mm. To keep the subsequent design models simple only a single nozzle of an inner diameter of 500 mm was placed in the cylindrical shell by a butt weld. The plate thickness of this nozzle was restricted from the consideration that the design pressure of the nozzle is equal to the shell.

A conventional design approach resulted in a design pressure of 8.3 MPa for both shell

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and nozzle, whereas application of the minimum damage curve of steel grade P500Q resulted in a burst pressure of 25.8 MPa. From these investigations the exaggerated actual safety margins can be seen.

For the derivation of improved safety factors for future design standards, the scattering within the minimal and maximal damage curves should be described with the aid of typical scattering of characteristic crack initiation values J_i of fracture mechanics tests. In that way, the natural variation of the properties of materials and thus the determination of the different load bearing capacities of components would have been taken into consideration. Based on several simulations of components in structure mechanics, which are actually meant to replace the experiments required for applying the probabilistic safety concepts, improved safety concepts have been derived as a result of large database, in accordance with the rules lined out in EN 1990.

The first series of comparative analysis has shown that this method can be used to determine lower safety factors than the method used up till now. With regards to this, the potential of the high strength steels in the construction of steelwork appliances can probably be used, if the safety factors based on probabilistic approach are applied.

Depending on the acceptance of these findings in the norm-setting committees, they will be considered for future drafts of the European design standard in civil and mechanical engineering.

4 Finding a solution in the social dimension

For a wide uptake of HSLA steels it is important that standards and norms for their safe application get developed. Despite the existence of new risk calculation models, getting reduced safety values accepted in the norm-setting committees is a complex process. In this process agreement on technical parameters and calculative models forms only part of the puzzle, together with institutional structure of and representation of interests in the norm-setting committee. As an example, issues of institutionalization and epistemology can be identified in the European Committee for Standardization (CEN). This committee is an important standard-setting organization, developing norms and standards in multiple areas for 31 European countries. CEN develops European standards for, for example, chemistry, food, health and safety, materials, and ICT that "are based on a consensus which reflects the economic and social interests of 31 CEN Member countries channeled through their National Standard Bodies [21]". This means that all member states of CEN are represented in the committees that formulate standards. Such standards are in principle voluntary and referenced in European directives, which therefore do not have to be updated as long as relevant standards are up to date. CEN standards are also implemented at the national level by the various standardization boards of the member countries. Any interested party can propose an issue on which it considers the development of a standard to be necessary, which is then drafted, made available for public comments, adopted through a weighted voting mechanism and published as an EN number. According to CEN, this process should be completed within three years, provided the application is approved and experts can agree on a standard.

In the case of HSLA steels the latter is considered to be quite a challenge, despite the value that the widespread use of such steels may have. While in-depth social science insight into the functioning of CEN has thus far not been substantively developed, two main strands of obstacles to the development of a norm for innovative steels that applies the risk calculation method described above can be postulated. In relatively broad terms, these can be described as institutional and epistemological complexities in the standard setting process.

As reported in the self-description of CEN cited above, the committee consists of representatives of 31 European member states who stand for the economic and social interests of each of these members. This indicates that, in an institutional sense CEN is not a committee that develops standards on a purely technical expert basis, nor is it intended to be. Instead, it forms the link between national standardization boards and

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the single European market and explicitly leaves room for the European tradition of policy compromises based on the principle of subsidiarity, that is, the notion that national states continue to exert power in areas where this is considered to be necessary or appropriate. It also leaves room for various member states to promote the competitive position of their own industries by expressing a preference for standards that are attached to national industrial practices or traditions. Most European countries have an industry sector in which their national economy is particularly invested and for which they thus have a strong sense of ownership or complicity that extends to the development and – particularly – maintenance of standards. Such national interests are not limited to economics, however, but also have socio-cultural, historical and geographical roots. In this context one can think of variation in European climates, expectations people have of product lifecycles, the compatibility of new materials with existing (infra-) structures, etc. These elements all contribute to diverging views on the requirements for a European standard about which the various national representatives will have to reach agreement.

A second institutional issue is the notion of European standardization and what it represents as such. The development of standards at the European level has been a conscious effort to achieve uniformity at a particular supranational level. This has significance of its own. One question could for example be why European standards are required, despite the existence of both national and global standards from the International Organization of Standards (ISO). In a presentation available on the CEN website some indications of the intentions underlying (European) standardization can be found (see ftp://ftp.cen.eu/cen/Services/Education/StandarDays/SD7/Day1/Vaccaro.pdf). Standards are for example expected to contribute to the creation of a single European market, facilitate easier access of new EU members to the Union, foster innovation in Europe and enhance the EU's competitive position on global markets. These objectives are in line with the dominant discourse of the benefits of European collaboration and may thus appear self-evident or unavoidable, but one can wonder whether these objectives are compatible with each other and with the representation of national interests cited above. As a thought experiment, one could for example consider the question whether innovation in high strength steels is not hindered by protecting economic interests of steel industries through existing standards. Moreover, the economic rhetoric presented by CEN itself effectively positions other perspectives out of view, such as the expected reduction of material and energy use, and thus more sustainable production process of high strength steels. This means that the production of European standards, mainly motivated from an economic point of view, strongly suggests and advances particular interests – of economic competitiveness and European integration – to be stimulated by the standards CEN develops.

Such institutional elements form one kind of obstacle to the development of standards that take into account the higher load bearing capacity in new steel grades. A second kind of obstacle is found at the level of epistemology and the kind of calculations and modeling different scientific communities deem plausible and acceptable. Different "epistemic communities" have different styles of thinking, doing research, describing results, etc. Similarly, standards for safety of steel are based on particular ways of approaching the question what constitutes safety and how to calculate it. New approaches to calculating safety and risk may, at least initially, be incompatible with existing approaches that may be dominant in the standard-setting community. What should be noted is that this is not merely a matter of not understanding a new model; epistemic differences speak to a much more fundamental level of perceiving and understanding the natural world and are therefore not easily resolvable by continuously explaining a new assessment model. Shifts from one epistemic approach, worldview or scientific "paradigm" to another take time and are as much a matter of organizational and generational shifts in scientific disciplines as of evidence (since exactly the question what scientific evidence is, is contested). In the context of developing standards, however, the issue

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of epistemology is not a purely theoretical one; the question is not about the reality-status of a risk assessment model, but about its functionality from economic, social, ecological and other viewpoints. In other words, the question is whether a risk calculation model can do the job of setting norms for "good" (safe, cost-effective, useful, and sustainable) materials.

Thus, both institutional and epistemic obstacles to the acceptance of HSLA steels and methods for calculating their safety are related to the boundary conditions of standard setting. Epistemology and institutionalization both contribute to a framework that describes which considerations can legitimately be part of a set of norms for particular materials. The most productive way of addressing social challenges to sustainable innovation in materials in the area of standardization is thus to question this framework and its underlying assumptions. Although our analysis here is based on exploratory research in standardization for materials and the standardization committee CEN, there are clear indications of the kind of professional engagement activities that could contribute to stimulating an alternative to the current framework. One option is to place issues of sustainability more explicitly on the agenda. Sustainability is a concept that is increasingly visible in policy arenas and the media, and may therefore be able to gain enough support to be included in the standardization framework. The significant financial benefits that can come from producing steel differently (shown in Fig. 2) could be another example. Point of such exercises is to build a coalition around a different perspective on standardization and norm-setting for steel that can draw on a wider set of resources than the epistemologically challenged evidence of a new calculation model alone.

5 Conclusions

- The European design rules for civil engineering belong to modern design codes for structural steelwork. However, the application of high strength steels is still hindered although these materials offer excellent strength and toughness properties. Nevertheless, the application of such modern materials is useful because they can significantly contribute to lightweight and resource-efficient design yielding to a better economy.
- Especially as European steel producers have concentrated on the development of quenched and tempered structural steel grades, the disadvantageous treatment of these materials should be avoided by the European design standards.
- A methodology is presented how to derive improved safety factors for steel constructions. The procedure is based on the application of a probabilistic safety concept. The innovative approach is to replace the required full scale experiments by damage mechanics simulations. Like this, an extensive cost and time saving potential can be raised. Nevertheless, one has to fear that the acceptance for the new procedures is not sufficient to guarantee a short-term consideration of the new findings in European design standards.
- Social obstacles to the development of standards for HSLA steels based on alternative models for calculating steel's safety are rooted in an institutional and epistemological framework that dominates norm setting. Institutional issues are, for example, the set-up of European standardization efforts around the representation of national interests and European integration and competitiveness. Epistemologically, a particular paradigm of safety modeling can lead to irreconcilable perspectives of what counts as evidence for safety.
- Confronting such social challenges to the development of new standards requires an effort at building coalitions for expanding and revising the standardization framework. Such an effort can be a lengthy and unpredictable process, however.
- In order to be able to deal with the challenges presented by the institutional context of standardization it is first of all necessary to get more profound insight into the way such institutions operate. Social science research addressing the operation of organizations such as CEN is

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therefore necessary for enhancing both social and technical aspects of sustainable design.

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