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Structural requirements and material solutions for sustainable buildings

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Abstract – Especially in OECD countries, the reduction of primary energy consumption is a major task to avoid further increase in CO_2 emissions. Since 37% of the annual energy consumption is related to the building sector, it is a major challenge for the future to develop methods for significant improvement of the energy efficiency of building design, construction and operation. It has to be noted that the development of sustainable buildings addresses both engineering and social aspects. From an engineering viewpoint methods to improve the ecologic efficiency of buildings by increasing the lifetime have to be provided. From a social viewpoint these new approaches must take the future needs of society into consideration. In addition, also governance structures and the regulatory framework for the construction and operation of buildings need to be modified in the direction of sustainability. The article will initially identify the major research topics for the development of sustainable design principles for buildings. Afterwards, structural requirements will be defined and translated into required property profiles for building materials. Herein, both mechanical and functional properties are of importance, so that approaches will be presented how to combine these properties in composite building materials. With respect to mechanical properties, new steels will have to be developed with an improved balance of strength and ductility, so that some promising steel design concepts will be shown. Additionally, new approaches for the failure assessment of these new steel types will be presented to enhance the exploitation of the characteristics of the innovative materials.

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In order to reduce the expected impact of the climate change, the global community needs to drastically reduce its CO_2 emissions within the first decades of the 21st century. Additionally, energy prices are continuously rising due to the shortage of resources and a steadily increasing global demand [1]. The key task for the – relatively wealthy – countries organised in the Organisation for Economic Co-operation and Development (OECD) is therefore to reduce their energy consumption and CO_2 emissions while maintaining the same level of wealth and a constant standard of living for their inhabitants.

Current media coverage of electric cars and renewable energies can easily invoke the impression that traffic and industry are the main energy consumers. However, the largest share of the world's gross energy consumption (Fig. 1) results from the construction and operation of buildings, which consume 37% of the total energy. Improving the energy-efficiency and the sustainability of buildings over their whole life cycle is therefore a crucial measure to effectively reduce CO_2 emissions and energy consumption in OECD countries.

Inhabitants of industrialised countries spent 90% of their lifetime inside buildings. Therefore, new building techniques affect all society members and need to be accepted among the population. Moreover, buildings are a long-time investment, whose structure and technology cannot be changed in short periods of time. This is shown by the fact that among existing buildings in city quarters only 10% are modern [2]. This means that a comprehensive concept for the emission reduction of buildings has to be found, which integrates the existing building stocks. The development of such a long-term concept

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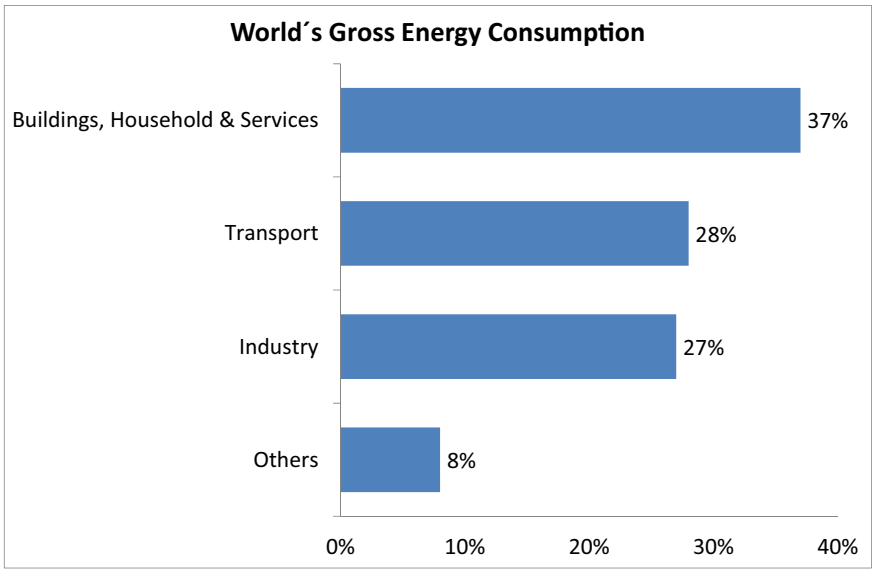


Fig. 1. World's gross energy consumption [1].

also has to take the future needs of society into consideration, which will be influenced by factors as, for example, demographic change.

Hence, the specifications for the sustainable building of the future have to be defined thoroughly before it is possible to develop technical solutions for it. As the above mentioned aspects show, this is a highly interdisciplinary task, which includes questions from engineering, social sciences, architecture, life sciences and information technology.

The technical realisation of these newly defined concepts will require new developments and significant research in all affected fields. Two disciplines are crucial to the performance of sustainable buildings: structural as well as material engineering. Substantial innovation in these fields will be necessary. The structural requirements for a sustainable building will be outlined in Section 2 and a detailed approach for material solutions in the field of multiphase steels will be given in Section 3.

1 Solution approaches for the development of sustainable buildings

Developing the sustainable building of the future addresses both engineering and social aspects. In engineering the relevant question is how to increase the ecologic efficiency of new buildings over their whole life cycle. Social sciences have to predict which requirements result from the demands of society and which non-technical factors can inhibit innovation towards sustainability of buildings.

The life cycle of a building comprises every step from the production of building materials to the demolition of the building. Currently, all life cycle phases are characterised by a high energy and material consumption. Recycling a whole building by reusing it for a different purpose is not common [3]. Industrialised, highly effective production methods, as they are applied in the automotive industry, are missing in civil engineering [4].

The most efficient measure to optimise the ecologic efficiency of buildings is an extended lifetime. This allows for a longer exploitation of the materials and the energy consumed in the building process. To enable a reasonable utilisation of buildings during an ultra-long lifetime, a flexible modification to multiple cycles of use, each fulfilling different purposes, is necessary [3]. This requires approaches for the recycling of building components, not only materials. To reach this aim however, it needs to be possible to modify the building during

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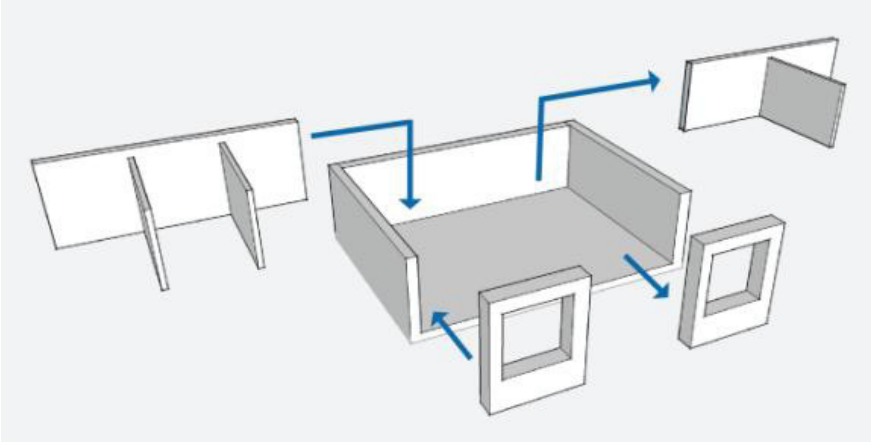


Fig. 2. Modularised building for flexible use as a principle of planning [5].

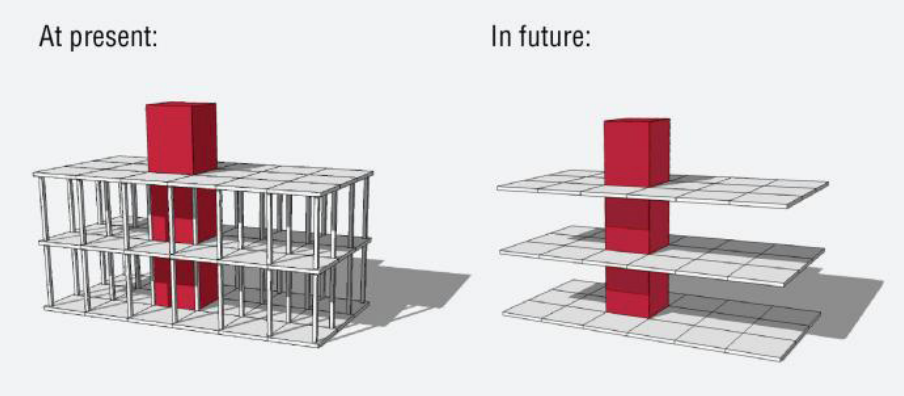


Fig. 3. Schematic illustration of a concept enabling flexibility by an open interior floor space.

its lifetime and to easily replace components with a shorter lifetime [3].

This long-term flexible use can be achieved by a modular building construction method. The assembly of a building in this concept consists of individual components, such as walls, facades or elements of them (Fig. 2), which can be easily exchanged and rearranged. Such a construction method also enables the introduction of industrialised manufacturing processes into civil engineering. These allow for an increased lifetime by standardised quality management and an optimised, energy-efficient production of components [4].

For structural and material engineering, this concept of modularised building results in new approaches and requirements. The approach in structural design to achieve the flexibility of indoor space division is that the interior floor space should remain open, increasing the usability of buildings (Fig. 3). The main challenges for structural elements are thus wide-span floor slab systems [6].

These floor systems require an extraordinary load-bearing capacity. However, to make optimal use of the energy management system, they also shall provide optimal heat storage and thermal insulation. In order to keep the flexibility of supply systems when changing the arrangement on indoor space, supply systems should be integrated in the floor slabs [7]. These requirements cannot be fulfilled by one single material. Therefore, new steels and concretes with excellent strength and toughness have to be developed so that they can be combined to fulfil the requirements of wide-span floor systems.

A concept to improve the characteristics of high strength low alloy steels (HSLA) is the addition of manganese combined with

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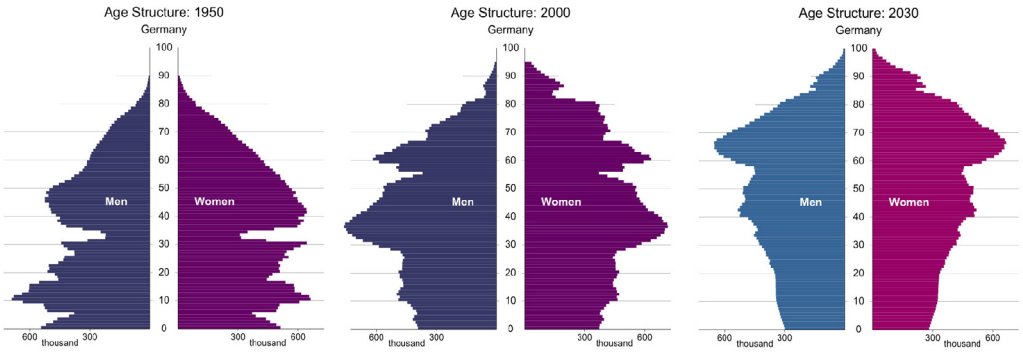


Fig. 4. Demographic distribution of Germany from 1950 to 2030 (projection) [9].

an ultra-fine microstructure [8]. These materials can be a solution to the structural requirements of floor slab systems in sustainable buildings. However, to be able to fully exploit the characteristics of these new materials and thereby ensuring resource-efficiency, new methods for failure assessment have to be found. They shall consider the specific characteristics of the newly developed steels. Detailed approaches for these questions are explained in Section 3.

However, before realising these new concepts it is necessary to determine whether this building concept can satisfy the future needs of society and will possibly be accepted by the population. One key factor for the future structure of society in Germany is the demographic change (Fig. 4), which will fundamentally alter the structure of society within the next decades [9]. The demand for age-based facilities will rise and future living conditions need to consider the possibility of external help. Consequently, the possibility of a flexible re-arrangement of living space would be beneficial, so that the living space can be adapted to changing requirements in different stages of the inhabitant's life [3].

A second aspect is the alteration of gender roles. Role models in families are changing and interact with a more dynamic working situation. This results in the need for flexible combination of private and office space. Flexible construction methods, which allow for easy modification of living space in order to adapt to changing socio-economic living conditions can therefore meet the future needs of society.

The regulatory framework, such as norms and standards, has an important effect on the applicability of newly developed technical progress. A first approach to this question in social sciences has shown that the modification of existing standards towards new, innovative materials is a difficult process due to competing interests of the involved parties [10]. It is therefore interesting to understand, how norms and standards can be influenced to favour sustainability, so that the newly developed failure criteria for innovative materials can be included in the standards.

In summary, the sustainable building of the future is characterised by a high flexibility, which is achieved by a modularised assembly and allows for a flexible adaptation to changing living conditions of its inhabitants. A long lifetime with several cycles of utilisation ensures its ecologic efficiency. The realisation of this concept is enabled by innovative materials and triggers therefore scientific challenges for the material sciences, which are exemplarily discussed in the subsequent section.

2 Challenges in steel design for sustainable buildings

The aim of efficient utilisation of natural resources has been persistently pursued for many years in materials science. Especially for the reason of current discussions about integrating sustainability verifications in the design guidelines of structural engineering, the efforts towards improved resource efficiency have even been intensified. The current development can be classified into two approaches. On the one hand, new materials

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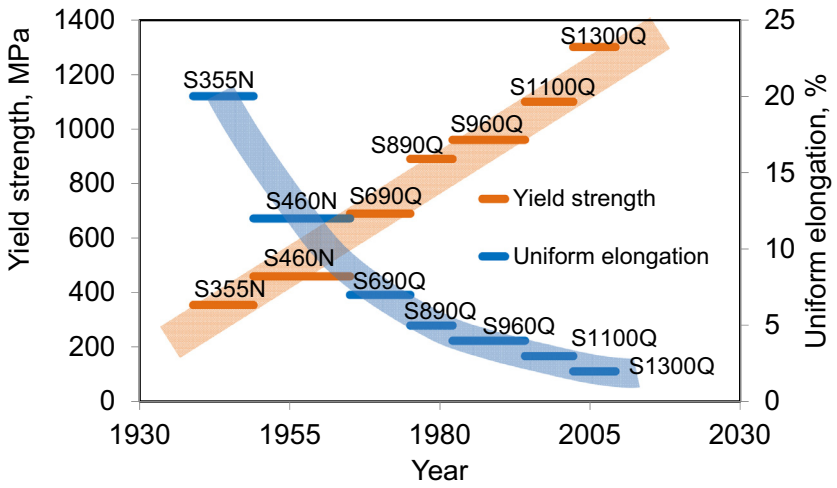


Fig. 5. Development cycles of HSLA steels and desired mechanical properties of the newly developed steel.

are developed which provide an optimally tailored property spectrum for the corresponding application, while on the other hand also efforts are undertaken to optimise the exploitation of mechanical properties by modification of underlying design regulations.

2.1 Providing new highly stress-resistant materials with optimally tailored property spectrum

For many years, the main development target for structural steels was increasing the material's yield strength. For this purpose mainly grain refinement through precisely controlled thermo mechanical treatment was applied on low carbon steels as this also resulted in improved weldability and low cost. However, due to the reduced carbon content compared to conventional structural steels the ultimate stress was not significantly affected by the applied measures, so that the available HSLA steels nowadays show a relatively poor uniform elongation (Fig. 5). Resulting from this, these steels actually do not fulfil the safety requirements in civil engineering which are expressed as yield-to-tensile ratios [11]. Consequently, for the future high strength structural steels with improved ductility compared to conventional HSLA steel have to be developed. These must also meet the building-industry specific requirements on the processing properties, e.g. weldability, and formability.

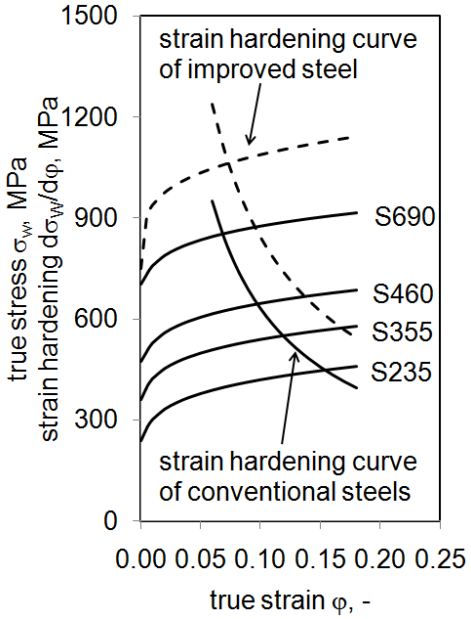


Fig. 6. Illustration of the Considère criterion and its consequences for steel development.

The conventional steel's decreasing ductility with increasing yield strength is explained by the Considère criterion. It argues that in a simple tensile test, the necking of the sample starts as soon as the flow curve and the strain hardening curve, its first derivation to the strain, intersect (Fig. 6).

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Consequently, improving the ductility of a structural steel on a given strength level requires to significantly improve the strain hardening behaviour.

The concept of improving the strain hardening behaviour of modern steels has been successfully demonstrated for cold formable steels for automotive application. However, in material design of such advanced high strength steels (AHSS), the focus is set on the modification of the strain hardening behaviour at large plastic deformations. This is due to the fact that on the one hand the plastic deformations in these processes are extensive and on the other hand, the energy consumption for the forming operations should be low. Hence, the concepts applied on AHSS must not simply be adopted for HSLA steels, but new materials design concepts should be invented which concentrate on the improvement of the strain hardening at small plastic deformations.

One possible approach to high strength structural steel with improved strain hardening behaviour is based on the idea to develop an ultrafine-grained duplex microstructure made of ferrite and retained austenite [8]. Resulting from the grain refinement, both yield strength and toughness properties will be improved compared to conventional grades of structural steel. The carbon and manganese enriched retained austenite additionally positively alters the toughness properties due to its face centred cubic crystal structure. Since the microstructure is composed of two phases with distinct differences in strength and ductility, especially at low plastic deformations there will be strong gradients in the local strain distribution, which can be expected to result in pronounced strain hardening behaviour.

The metallurgical concept is based on significant additions of manganese (5%–7%). On the one hand this goes along with solid solution strengthening, and on the other hand such alloys have been reported to belong to the group of air-hardening steels since the critical cooling rate to provoke a martensitic phase transformation is smaller than 2 K/min [8]. After quenching, a partitioning process shall be applied. For this purpose, the alloy is intercritically annealed so that both carbon and manganese diffuse into the austenitic phase. This heat treatment stabilises both the austenitic and the ferritic phase, so that after cooling the desired microstructural configuration is achieved.

2.2 Full exploitation of new steel's profile by enhanced failure simulation

Building elements are dimensioned according to the requirements of the corresponding standards. If the standards do not appropriately consider the characteristics of new materials they can be exposed to significant disadvantages, as can be shown for high strength low alloy steels in civil and mechanical engineering [10].

In civil engineering, the current standards define the load bearing capacity of components by strength assessment [11]. This means that there is a limitation of stresses in the component and plastic deformation is avoided. Consequently, optimised ductility characteristics have no influence on the allowable loads for building components. However, to be able to realise the wide-span floor construction in sustainable buildings, the optimised characteristics must be fully exploited. Relevant for the dimensioning of building components are hereby the nominal characteristics of materials, which must be guaranteed by the material supplier and are defined in European standards, e.g. for structural steels in EN10025. These can be strength, yield stress, upper shelf ductility and minimum transition temperature. In order to improve the exploitation of material characteristics it is therefore necessary to predict the critical loading conditions of a material while referring to the nominal material values.

The strength assessment considers plastic yielding as the critical limit state. However, for high strength steel, ductile failure occurs at significantly higher loads than the onset of plastification. As long as brittle failure is excluded by ensuring an adequate transition temperature of the material, ductile crack initiation can alternatively be considered as limit state of the material for strength assessment [10]. By this approach the exploitation of the new, highly efficient materials can be optimised. The relevant

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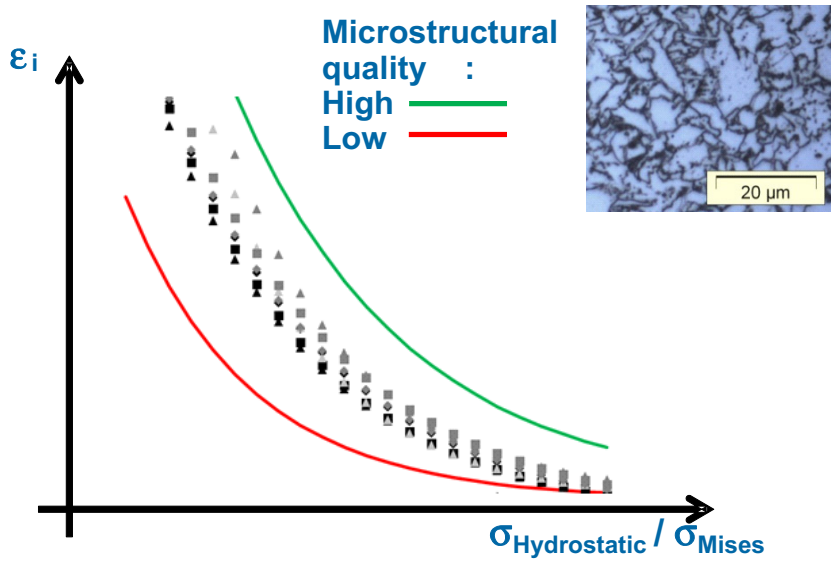


Fig. 7. Schematic illustration of the concept for the derivation of damage curves by means of cell-model simulations with the GTN damage model, the grey dots indicate the scatter of experimental results.

nominal value to refer to is the ductility at room temperature.

To characterise ductile failure of steels macroscopic damage criteria based on classical continuum mechanics failure models, such as the concept of Johnson-Cook [12], can be applied. It describes the characteristic failure strain for ductile failure as a function of the stress state. This model has two shortcomings. Firstly, the model is usually calibrated in experimental tests on real materials, whose characteristics mostly exceed the minimum guaranteed nominal values, such as ductility. Additionally, it describes the failure strain, which differs from the characteristic strain for ductile crack initiation. A concept including the latter however has advantages in describing the failure behaviour more adequately [11].

An approach to overcome these difficulties is presented in [10]. Münstermann et al. describe a procedure to derive the damage curve for ductile crack initiation by cell model simulations, which contain the micromechanical failure model of Gurson, Tvergaard and Needleman (GTN) [13, 14]. A minimum damage curve, describing the lower bound load-bearing capacity of the material is correlated to the nominal ductility by the simulation of Charpy tests. Hereby, the GTN-parameters are calibrated, so that the nominal ductility is reached. With this calibrated set of parameters, the damage curve is derived by the simulation of unit cells. Some of the GTN-Parameters hereby are correlated to microstructural characteristics, such as the inclusion content (Fig. 7). This concept has successfully been implemented for the failure assessment of pressure vessels and might provide a solution for steel constructions in sustainable buildings.

The Johnson-Cook damage curve and the GTN failure model characterise the stress state by the stress triaxiality η, which is the ratio of first to second invariant of the stress tensor.

$$\eta = \frac{\sigma_{\text{Hydrostatic}}}{\sigma_{\text{vonMises}}} = \frac{1.\ \text{invariant}}{2.\ \text{invariant}}$$

First and second invariant of the stress tensor describe a circle in the principal stress state, whose centre is defined by following the hydrostatic axis for the value of the hydrostatic stress, the first invariant. The circle is situated in the deviatoric plane, which is orientated perpendicular to the hydrostatic axis. The radius of the circle is defined by the second invariant of the stress tensor, the von Mises stress (Fig. 8). The Johnson-Cook damage curve and the GTN-model treat all stress states situated on this circle equally.

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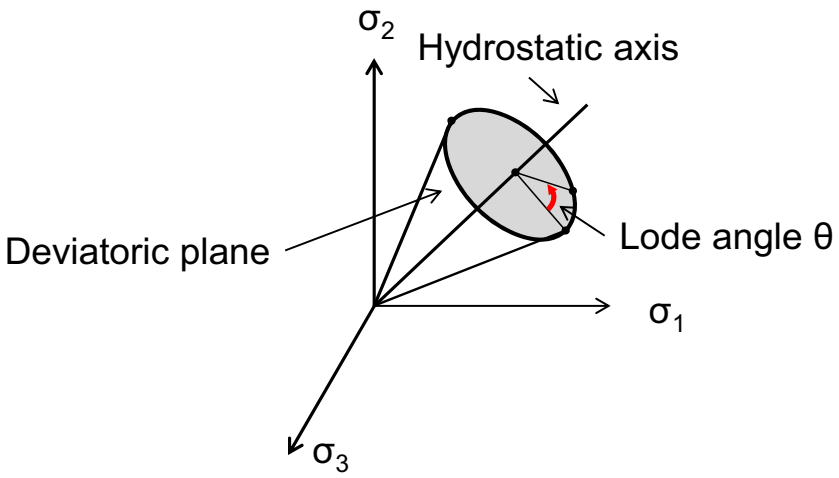


Fig. 8. Schematic illustration of the additive composition of the stress vector of hydrostatic and deviatoric part, finally defined by the Lode angle.

However, new developments in the past five years have shown that a full consideration of the stress tensor is necessary for the simulation of ductile failure because the third invariant has significant influence on ductile failure [15].

To precisely characterise a stress state in this principal stress space, the location of the stress state on the circle in the deviatoric plane has to be considered. This is possible by the Lode angle θ, which is defined in dependence of second and third invariant of the stress tensor (Fig. 9).

$$\cos(3\theta) = \left(\frac{2.\ \text{invariant}}{3.\ \text{invariant}}\right)^3$$

Bai and Wierzbicki proved that the Lode angle has significant influence on the ductile failure behaviour of metals [15]. Instead of a damage curve, the Lode-angle dependent criterion describes a 3D failure strain locus in the space of stress triaxiality and Lode angle (Fig. 9). It can be seen, that the Lode angle has significant influence on the failure strain and it is therefore necessary to consider this value for a full, safe exploitation of new materials' characteristics. The parameters for the Bai-Wierzbicki (BW) failure model are calibrated in experiments with specimens of various shapes and resulting stress state. Thus, the BW failure locus has the same disadvantages as the original Johnson-Cook damage curve, since it refers to failure strains and to real material values, not nominal values.

The first disadvantage can be eliminated if the locus is calibrated to represent the ductile crack initiation [16]. However, a calibration to nominal values is difficult in the model of Bai and Wierzbicki, since there are many parameters, that cannot, contrary to the GTN model, be correlated to the microstructure.

The challenge for the future development of reliable damage criteria for the full exploitation of new steels for sustainable buildings is therefore a failure criterion considering the Lode angle, which can be correlated to the nominal values guaranteed by steel producers.

The most promising approach for this is a modification of the GTN damage model towards Lode angle dependence. There are already several concepts available in literature [17, 18]. Aiming at an optimised exploitation of newly developed steels by full exploitation of their characteristics, the existing formulations need to be evaluated with respect to an effective and physically based calibration procedure. To allow for an effective derivation of the crack initiation locus by cell model simulations it is necessary to identify the relevant parameter sets. The GTN parameters are firstly calibrated by characteristics of real material samples, such as the volume of non-metallic inclusions and Charpy energy. To take the nominal values into consideration, the calibrated parameter set is then modified in iterative simulations

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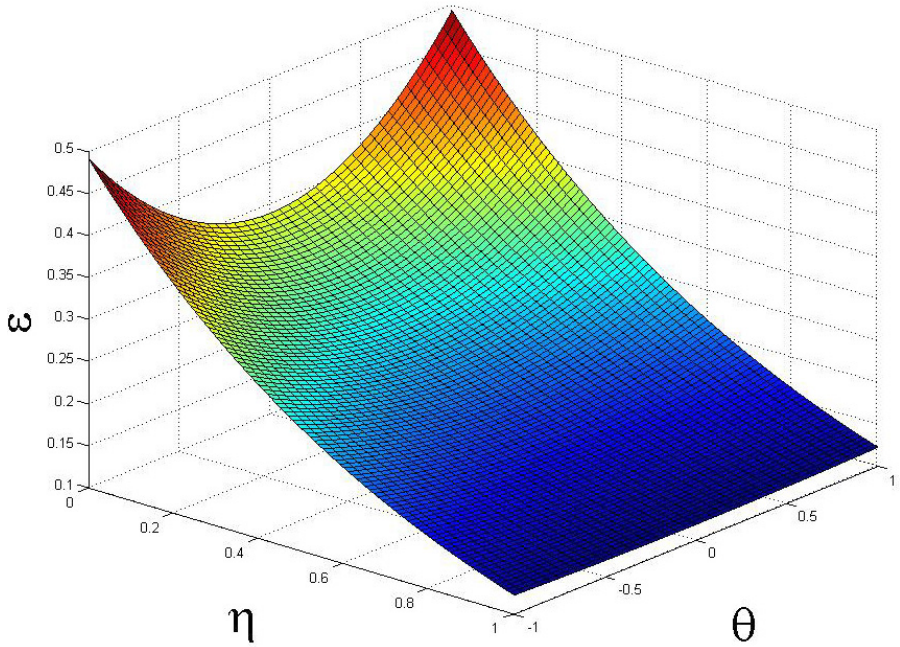


Fig. 9. Ductile crack initiation locus for the pressure vessel steel P500Q in the space of stress triaxiality η, the normalized Lode angle parameter θ and the equivalent plastic strain.

to meet the nominal values of the material. By this, a lower bound ductile crack initiation locus can be defined, which allows for a safe dimensioning of building components.

By investigating the different results of dimensioning innovative building components with the design rules according to the current standards and the newly developed, damage-based simulation method a profound data basis for a discussion of the adaptation of current standards and norms towards new methods can be created.

3 Conclusion and outlook

One of the most effective measures to reduce energy consumption and CO_2-emission in OECD countries is the energy-efficient construction and operation of buildings. New, sustainable buildings will be characterised by a modular construction method that allows for a long lifetime with multiple cycles of use. To enable this concept, a wide-span floor construction is necessary to enable a flexible re-arrangement. These floor systems require new, innovative materials with an improved balance of strength and ductility.

In construction steels this concept can be realised by optimising the metallurgical concept of HSLA steels. This can be achieved by significant additions of manganese, which enable new strain hardening mechanisms. In order to fully exploit these new materials and thereby ensure an efficient utilisation, the standards for the dimensioning of building elements with these new steels must be adapted adequately. To do so, it is necessary to reliably predict the failure states of the new materials. It is beneficial to correlate the failure prediction to the nominal material characteristics guaranteed by the steel producer, such as ductility. This is possible by applying continuous damage models, such as the Johnson-Cook damage curve. However, a full consideration of the stress tensor in the failure model is necessary. Therefore, it is necessary to develop a failure model that includes Lode angle dependence and can be calibrated to meet the nominal values for steel types. By comparing the dimensioning of innovative building components by this new method and according to current standards, it is possible to provide a data basis for the discussion on the adaptation of standards in civil engineering towards sustainability.

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