An Upper Shelf Criterion for the Choice of Steel based on Fracture Mechanics

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Summary

Steel members which are designed plastically require sufficient strain capacity to ensure the formation of the plastic resistance. In case of earthquake loading brittle fracture of welded connections in steel moment frames may occur prior to the formation of plastic hinges. However, the utilization of material reserves plays an important role especially in seismic design due to its energy dissipation. Yet, the minimum required strain capacity still cannot be quantified. Thus, the objective of the research project “PLASTOTOUGH” [1] was to establish an approach for the quantification of the upper shelf toughness to allow for a safe plastic design of steel structures using modern construction steels and to develop a sustainable method for the choice of steel material. Once the steel material provides adequate ductility values, the service life of structures can be extended effectively. Therewith the need to replace damaged structures with insufficient material properties will be minimized and the maintenance costs for buildings or bridges will be decreased in the future.

This paper is the first of two parts giving an overview over the research work performed within the project for monotonic loading. The second part concerning seismic loading is presented in the subsequent paper “*An Upper Shelf Criterion for the Choice of Steel for Seismic Loading*”.

Keywords: Upper Shelf Criterion, Fracture Mechanics, Damage Mechanics, Seismic Loading

1. Introduction

General design rules in order to achieve mechanical resistance and stability of steel structures are valid at room temperature and rely on elastic-plastic material behaviour. For safety reasons plastic strain redistribution is necessary especially at local stress concentrations such as welded attachments, cut outs, nozzles and also in frames to enable moment redistributions by formation of “plastic hinges”. The material requirement resulting from these design rules demand therefore significant strain capacities of the steel and weldments. In terms of toughness the material requirement must be expressed as a suitable upper shelf criterion. The structure is to exhibit sufficient deformation capacity and the material should provide enough ductility on the upper shelf region of the temperature dependent toughness curve.

However, the assessment of the required toughness on the upper shelf is still missing and therefore plastic design both for quasi static actions and for time varying actions is limited to structures not exposed to very low temperatures. Therefore solutions have been worked out for adequate toughness proposed for

- plastic design of structures subjected to quasi static loading by extending the toughness criteria already given in Eurocode 3,
- plastic design of structures subjected to time varying loads which are developed in particular for structures subjected to seismic actions.

The new unified design standards for steel structures in Europe in EN 1993 require for safe design of structural components two assessment verifications, the

- ultimate limit state verification, based on the assumption that sufficient material ductility is provided and no brittle fracture occurs.
- choice of material to avoid brittle fracture and to guarantee sufficient toughness properties.

For the latter, a method is given in EN 1993-1-10 for the choice of material which is based on linear elastic fracture mechanics. This method relates to toughness properties in the lower shelf region of

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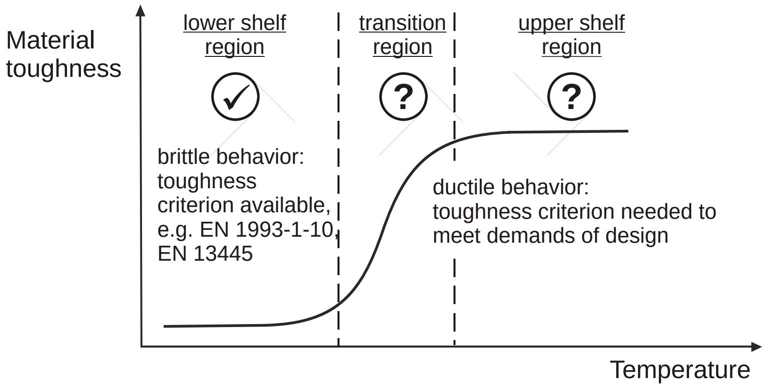
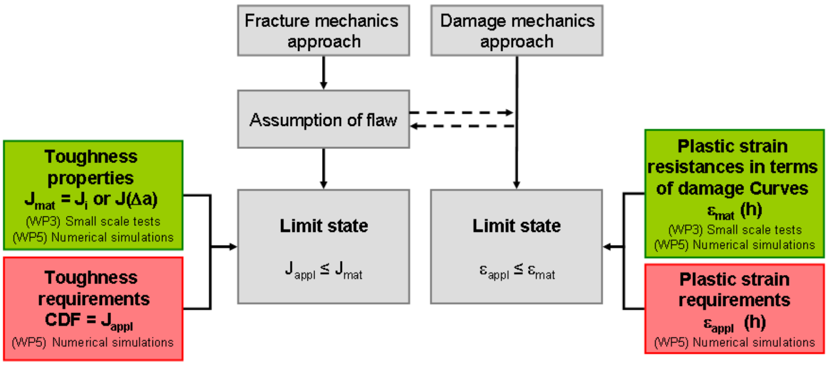
the toughness-temperature curve that are associated with elastic design.

For quasi static actions no specific toughness criteria exist so far for steels to be used in plastic design. EN 1993-1-1 only recommends ductility criteria which are still debated as they are based on engineering judgements. Beside these ductility criteria concerning the material itself the European standards give global requirements for the endurable plastic rotation of a connection. However, for these design situations an upper shelf toughness criterion for the choice of material is still missing.



2. Proposal for an upper shelf criterion for monotonic loading

An upper shelf toughness criterion based on fracture mechanics has been proposed that allows safe plastic design of steel structures using modern constructional steels subject to monotonic loading [1]. Using this approach a limit state between the requirements arising from the applied loads and the resistance given by the material in terms of crack driving forces is defined. The figure below shows the verification scheme for monotonic loading and also the scheme for non-monotonic loading, e.g. seismic loading (presented in the subsequent paper "*An Upper Shelf Criterion for the Choice of Steel for Seismic Loading*").



As the plastic behaviour of the material has to be taken into account the J-Integral concept was applied for fracture mechanics approaches (FMA) to determine the toughness requirements J_{appl}. Extensive numerical investigations have been performed with the FE- models calibrated and validated by means of large scale tests. The derived results show that the developed numerical models are adequate tools to determine the fracture toughness demands of a structural member or detail in the upper shelf. By the numerical models the fracture mechanics parameters J_{appl} have been derived for various details in dependency on the global deformation in terms of global strain or global rotation. Based upon these results the action side of the limit state could be quantified.

For the FMA the application of the upper shelf criterion is strongly dependent on the availability of a verified materials resistance (fracture toughness) value J_{mat}. Several available approaches which are based upon either the Charpy toughness CVN_{US} in the upper shelf or on the T_0-temperature have been investigated for applicability and showed good agreement with the test results of the large scale tests. But as the upper shelf toughness is not demanded by the product standards like EN 10025, certified links from the transition zone to the upper shelf are still missing.

Finally, an upper-shelf criterion based on the FMA in form of the limit state $J_{appl} \leq J_{mat}$ is proposed which has proven to be applicable for structures subjected to monotonic loading situations.