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Numerical and experimental analyses of damage behaviour of steel moment connection

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ABSTRACT

Plastic design allows the exploitation of the full resistance of steel structures by taking advantage of stress–redistributions due to plastic strains exceeding the yield strain. Especially in seismic design the utilization of material reserves and the formation of plastic hinges play an important role. In devastating earthquakes in Northridge (USA) and Kobe (Japan) brittle fracture of welded connections in steel moment frames occurred prior to formation of plastic hinges and utilization of plastic material reserves. The subsequent research works resulted in improved design rules and recommendations for these kinds of failure. But to guarantee sufficient ductile performance of these connections also in the upper shelf region, plastic and earthquake resistant design rules should take into account degradation of strain capacity and toughness properties due to quasi static and especially seismic loading.

In the scope of the current European project "Plastotough", the main objective is to derive quantified toughness design rules in the upper shelf based on the strain requirements opposed to strain capacities. This paper gives an overview over the research work in performance and shows recent results from experimental and numerical analyses performed within this project for monotonic and cyclic loading.

1. Introduction

The strong seismic events in Northridge (USA, 1994) and Kobe (Japan, 1995) caused severe damages of beam-column connections by brittle fracture. In Kobe during the 1995 Hyogoken-Nanbu earthquake, the damage of the steel frame buildings was governed by the fracture process consisting of three parts, ductile crack initiation at the weld toe representing hot-spot concentration, subsequent stable crack growth and sudden explosive crack propagation in the brittle mode [1]. The brittle fracture occurred before the stress–redistribution in the beam and formation of plastic hinges were possible. The causes of damage were too high assumed design values for the material resistance due to unconsidered strain rate effect, large scale cyclic straining and residual stresses. These may lead to degradation of the material toughness and ductility especially in the presence of mechanical and metallurgical defects and heterogeneities, e.g. welding defects or stress risers in the local brittle zones of weld or heat affected zone.

In recent years many research studies [2–4] have been initiated in the USA and Japan with the objective to investigate deformation and fracture behaviour of steel moment connections with respect to seismic loading. The results of these investigations were improved design rules for connections, recommendations concerning quality control of welding, the

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amendments of existing seismic codes [5] and development of new engineering methods, e.g. WES 2808 [6]. Parallel to research activities in the USA and Japan, the European scientists have recognized the necessity to revise European seismic codes especially Eurocode 8. Within the project called "Recos" [7,8] the seismic behaviour of beam-to-column connections were examined in dependence of different influences, e.g. strain rate effects, connection typology, column size, etc.

The major aim of the European project "Plastotough" started in 2005 is to define the limit state for structures subjected to certain plastic strain requirements and to derive design rules for the choice of material for these structures based on an upper shelf criterion by applying fracture (FMA) and damage (DMA) mechanics approaches. One of the innovations compared to previous projects is the use of damage mechanics models, which allow for prediction of ductile crack initiation and propagation under monotonic and cyclic loading. In this context, it should be noted, that plastic design rules for monotonic and cyclic loading conditions based on the earthquake situation will be derived for the limit states defined by types of failure, such as local buckling or ductile tearing. The modifications of these rules by taking into account the results from investigations on the strain rate effects and the process of transition from ductile to brittle fracture are planned within the subsequent project.

The first part of the paper gives a short overview over the available ductility criteria in plastic design of steel structures and highlights the lack of upper shelf toughness criteria in the European standards. In the second part the applied models are presented where beside well established fracture mechanics models also damage mechanics models are shown. Afterwards, the investigated plate and beam materials are characterized.

Subsequently the results from small scale tests and their numerical utilization for the calibration of damage models are described in detail. Furthermore small scale tests are performed to obtain the basic characterization of the analysed steel grades and to determine fracture mechanics characteristic values. The simulation of ductile fracture is performed by applying different models in dependence on the type of loading (monotonic or cyclic). The widespread GTN (Gurson–Tvergaard–Needleman) damage model is used in case of monotonic loading. Once damage parameters are identified, this damage model can be applied for different geometries. In case of cyclic loading features like cyclic hardening, softening and Bauschinger effect are taken into account by the extended GTN model, so called LPD (Leblond–Perrin–Devaux) model. Additionally the effective damage concept according to Toyoda [22,23] with "advanced two-parameter criterion" is also evaluated with respect to predict ductile crack initiation in steel structures under cyclic loading. The parameters necessary for cyclic damage models are obtained from deformation controlled tests on notched round bar tensile specimens and CT specimens with blunted notch.

The first results from large scale tests are presented in the next part of the paper. These tests are performed with wide plate specimens under tension and beam-to-column connection under bending to examine deformation and fracture behaviour in terms of strain, rotation and load bearing capacity. By means of these test results, the numerical models are calibrated and optimised with respect to global load–deformation behaviour and crack initiation. Additionally results from large scale tests are used to demonstrate the transferability of the damage parameters and fracture mechanics characteristic values determined by small scale tests.

The last part of the paper deals with the numerical simulations with FMA and DMA. Both approaches will be used for parametric studies to determine toughness and strain requirements by varying crack sizes, steel grades, type of loading and geometry of joints and members. The results should allow for the development of general rules valid for the parameter range investigated. Within DMA, the evolution of damage in the welded connection is demonstrated by the LPD model in dependence on different crack size and loading amplitude.

2. Ductility and toughness requirements in plastic design of steel structures

Plastic design is used to take advantage of stress–redistributions due to plastic strains exceeding the yield strain. Such plastic strains may occur with different spatial extensions and magnitudes, as it is shown in Table 1 for beams in bending.

The plastic design of steel structures is mainly applied in two areas:

Table 1
Levels of plastic strain requirements.

Level	Type of analysis	Resistance of beams	Resistance of connections
1 Plastic strains only local e.g. adjacent to holes	**Elastic** No moment redistribution	**Elastic** distribution of stresses in beams	Local plastic strains resulting from assumptions for simplified "elastic" distribution
2 Plastic strains limited to the exploitation of full cross sectional resistance	**Elastic** No moment redistribution	**Plastic** distribution of stresses at one point of the structure at a time that receives the maximum elastic moment	Local plastic strains yielding from plastic redistributions of forces in a connection
3 Plastic strains limited to plastic rotation requirements for exploitation of full resistance of structure	**Plastic** Moment redistribution	**Plastic** distribution of stresses at more than one point of the structure at a time effecting plastic moment redistributions by rotations	Plastic distribution of forces together with rotations permitting also plastic redistributions