Journal of Constructional Steel Research 115 (2015) 407–416

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

# Welding of girders with thick plates — Fabrication, measurement and simulation

H. Pasternak, B. Launert *, T. Krausche

*Brandenburg University of Technology, Cottbus, Germany*

ARTICLE INFO

*Article history:*
Received 7 April 2015
Received in revised form 24 July 2015
Accepted 27 August 2015
Available online 14 September 2015

*Keywords:*
Welded plate girders
Welding simulation
Residual welding stress
Load capacity

ABSTRACT

This article presents experimental and numerical results of the fabrication of welded plate girders under workshop conditions. Main concerns are the prediction of imperfections with the aid of simulation tools and/or simplified engineering models. Their impact on the component design is evaluated in a case study. Special focus is put on the effect of residual welding stress. For this, different simplified distributions are compared with results from welding simulation. The findings confirm the thesis that present recommendations on the implementation of weld-induced imperfections must be rated conservative. This suggests that it is necessary to establish new models. Guidance on future problems in this context will be given.



## 1. Indroduction

In steel construction, usually the production contains two stages: the manufacture of parts under workshop conditions and the assembly on site. The former can be partially automated and has a much higher level of reliability compared to site welds. This article addresses the manufacture of such girders and proceeds to the production in the factory and the simulation of the welding process. Results in terms of residual stress and distortion are given and compared with typical engineering models. The validation of models is based on experimental data obtained during and after the manufacture. For a subsequent capacity analysis results are idealized and then implemented as initial conditions. The comparison of different models allows a review of recent standards. All results were obtained in the scope of a common research project of Brandenburg University of Technology and the University of Braunschweig (ifs).

## 2. Manufacture and measurements

The manufacture of the girders was performed under workshop conditions. Fig. 1 documents the geometry of the test specimens. Since the project consists of two parts, all examined girders received additional preparation for the assembly of two components in a Z-joint. Below, only the girder fabrication is discussed. The length of specimens was chosen with respect to the formation of a stationary stress state representative for girders with long longitudinal welds. The source materials are sheets of P355NL2. The sheets were delivered cut to size and with weld preparation (EN ISO 9692). To account for the assumption of an approximately stress-free state, all sheets were saw cut. This was confirmed by measurements prior to welding [1]. For further information on the influence of the cutting procedure, particularly if the use of concentrated amounts of heat is involved (e.g. flame or plasma cutting) see [2]. Thickness is 30 mm for the upper and lower flange and 15 mm for the web. Flange width is 500 mm and web height 800 mm. Due to the assembly of girders, which was realized as a second part of the project, all dimensions are in accordance with the restrictions given by the testing facility. The results for the assembly of girders can be found in [1].

Welding of fillet welds is performed in one layer with a throat thickness a = 5 mm. The process 135 (EN ISO 4063), metal active gas welding (MAG) with solid wire electrode, was used, because this is the most widely used process for factory fabrication work. An overview of the parameters is shown in Table 1. A total of 6 girders were manufactured. The fabrication took place in a manufacturing company in Dessau, Germany. Fig. 2 presents an example for the girder manufacture. No preheating was performed.

Fig. 3 shows the macrosection of a T-joint, which was welded with the same parameters as recorded during manufacture. According to the classification in EN ISO 5817, welds correspond to quality level B. The quality level, indicated by letters B (highest requirement), C or D (lowest requirement), specifies the quality of a weld based on type, size and number of irregularities. For steel constructions, EN 1090-2 contains additional specifications, indicated by the execution class (EXC) 1 to 4. The execution class can be defined for the whole structure or parts of the structure.

The welds were deposited manually one at a time. In practical applications with long continuous welds this is realized fully mechanized. The manufacture was monitored. The temperature was measured

* Corresponding author.
*E-mail address:* benjamin.launert@b-tu.de (B. Launert).

http://dx.doi.org/10.1016/j.jcsr.2015.08.037
0143-974X/

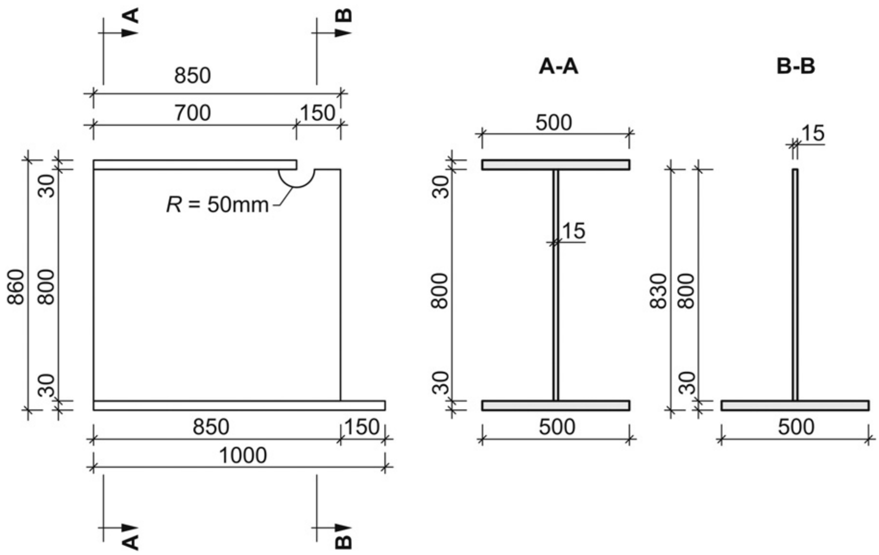


**Fig. 1.** Geometry of the specimens (note: the assembly of girders in a Z-joint is presented in [1]).

using type K thermocouples (range of temperature up to +1100 °C, for a short time up to +1300 °C). The temperature cycles are important to calibrate the heat input to the numerical model in Section 3 (e.g. efficiency). During the whole process distortions were also measured using inductive displacement sensors. Figs. 4 and 5 present temperature and distortion measurements representative for the testing of girders P355NL2. After welding residual stress was measured using X-ray diffraction (XRD). This method is based on measuring the diffraction angle, which is used to determine the interplanar spacing. Mechanical stress leads to very small changes in the lattice spacings only (<0.1%); therefore the diffraction angle must be determined with an accuracy of about 0.01 to 0.5°. The penetration depth is strictly limited (up to 5 μm), which is why results are restricted to the surface. Because of the dimensions a mobile diffractometer from ifs was used. Stress distributions longitudinal and transverse to the weld seam direction were determined. The data are important input quantities for the validation of numerical welding simulation models. The evaluation of experimental data has shown that results are comparable for all girders manufactured [1].

## 3. Welding simulation

### 3.1. Theoretical principles

The welding simulation has made a large progress in recent years. It allows the understanding of complex interactions during welding and cooling and thereby a more targeted optimization of the design. In the following, aspects of structural welding simulation are discussed. The macro behaviour under local heat input is simulated. The simulation can be performed using different multi-purpose or specialized software tools. Fig. 6 illustrates the typical calculation flow.

One of the basic assumptions is the weak coupling between thermo-physical and thermo-mechanical sub-models, i.e. temperature field, composition of microstructure and mechanics are determined in separate runs. The thermal analysis is based on the solution of the heat transfer equation. The heat source is idealized using mathematical models describing the distribution of heat. The most typical approach is presented by Goldak [3]. The geometric parameters of the source distribution are calibrated based on experimental data (melt zone and thermal cycles). The heat is dissipated by thermal conduction within the component as well as radiation and convection on the surface. Thermo-physical data such as thermal conductivity, specific heat and density are temperature dependent and therefore needed as a function of temperature. During phase change, a considerable amount of heat is released or absorbed (latent heat), causing a strong non-linearity in the specific heat function. Instead usually the specific or volume specific enthalpy function is used.

In a fully transient analysis the temperature field is transferred to an adequate mechanical model (the same mesh, but different element types, material properties and boundary conditions) for each time step. The mechanical solution is particularly time consuming. Input quantities are the calculated temperatures (or thermal strains respectively) and, for models taking into account the transformation of the microstructure, also transformations strains (resulting from the volume change during austenite transformation) and plastic strains due to the effect of transformation plasticity. To account for phase transformation effects different semi-empirical and empirical models can be used. The

**Table 1**
Overview of manufacturing parameters (P355NL2).

| I [A] | U [V] | $v_{Weld}$ [cm/min] | $v_{Wire}$ [m/min] | Welding process | Welding position | Filler material |
|---|---|---|---|---|---|---|
| 280–290 | 33 | 28.57 | 10 | 135 | PB | G4Si1 |

**Fig. 2.** Manufacturing under workshop conditions (Stahlbau Dessau GmbH & Co. KG, Germany).