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Shear resistance of longitudinally stiffened panels—Part 1: Tests and numerical analysis of imperfections

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Abstract

This paper deals with the results of four full-scale tests, numerical simulation of tests and initial geometric imperfection analysis for longitudinally stiffened panels in shear. The tests examine the influence of varying position and bending stiffness of one trapezoidal longitudinal stiffener on the panel shear resistance and its buckling behaviour. The stiffeners were designed such as to obtain both global and local buckling shapes. Numerical simulations (FEA), based on the test girder geometry, the measured initial geometric imperfections and elastic–plastic material characteristic from the tensile tests, demonstrate a very good agreement with the tests. The initial geometric imperfection study on different verified numerical models shows a limited sensitivity of the panel shear capacity to any kind of imperfection shape variation with amplitude at the allowable fabrication tolerances. Finally, the paper offers some ideas for modelling geometric imperfections with regard to the design or research demands.

Keywords: Plate girders; Tests; Shear loading; Longitudinal stiffeners; Stiffened panels; Buckling behaviour; Initial geometric imperfections

1. Introduction

Thin walled girders used in modern steel and composite bridges are usually stiffened with several transverse stiffeners, dividing the girder into panels, and a few trapezoidal longitudinal stiffeners along the web. The shear capacity of longitudinally stiffened panels can be significantly increased, especially in the case, when these stiffeners possess sufficient bending stiffness to induce local buckling shape within sub-panels. In the case of weaker longitudinal stiffeners the panel fails predominantly in a global buckling form. Furthermore, longitudinal stiffeners with closed cross-section are more efficient than open ones, since for the same welding costs a larger portion of web is reinforced and their torsional rigidity is much higher.

In the 1960s, after a few tremendous bridge collapses had happened, systematic research work on panel shear capacity was initiated and at first only unstiffened and transversally stiffened panels were studied. Based on shear tests many researchers (e.g. [1–7]) proposed their own mechanical model to assess the panel's post-critical shear capacity with the formation of an appropriate diagonal tension field in the panel and an adequate plastic frame mechanism of the supporting flanges and transverse stiffeners. In general, models differ in the definition of the tension field and in the position of the plastic hinges in the frame mechanism.

In the 1970s and 1980s some tests were carried out also on longitudinally stiffened panels (e.g. [8–13]). In general, the proposed mechanical models take into account two extreme situations: either the formulation of one tension field throughout the whole panel, where the longitudinal stiffeners are considered only at the determination of critical shear force ("Cardiff model" [9]), or the formulation of several tension fields, one for each sub-panel, where the longitudinal stiffener should provide sufficiently rigid support (models of Ostapenko and Chern [14] or Cooper [15]). The first case can be referred to as *global buckling* and the second as *local buckling*. However, since the stiffness of the longitudinal stiffener may vary, the failure mode may vary from one extreme case to another.

A method by Höglund took into account also the stiffener bending stiffness. His rotated stress field method was originally

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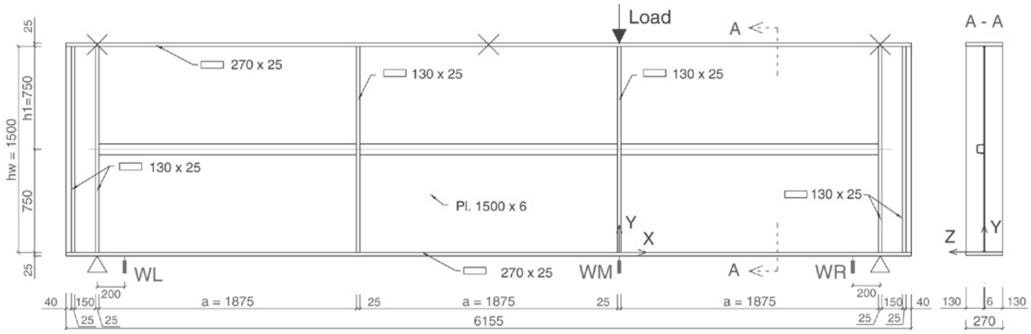

Fig. 1. Girder geometry — Girder 1.

developed for unstiffened webs [6] and was later extended also for panels with longitudinal stiffeners [16,17]. Since this method is simple to apply and among all the proposed methods it gives the best agreement with the whole set of available tests on short as well as long panels, Höglund's approach was accepted as the basis for design rules in the new Eurocode on plated structural elements — prEN 1993-1-5 [18]. However, except for four tests on closed triangular longitudinal stiffeners in [13] the method was verified exclusively with tests considering open flat stiffeners [16].

In order to obtain more detailed information on shear buckling of panels with closed longitudinal stiffeners, a new research project within the partnership between the University of Stuttgart and the University of Ljubljana was carried out, resulting in a Ph.D. thesis [19]. The research covers both experimental work, carried out at the University of Stuttgart, and numerical analysis performed at the University of Ljubljana. Four full-scale tests served to verify the numerical models, on which a variety of stiffener and panel parameters were studied in detail. In order to obtain a realistic panel shear resistance, the most unfavourable shape of initial imperfections has to be introduced in the FE model with the amplitudes referring to allowable fabrication tolerances. As opposed to unstiffened panels subject to normal stresses, the most influential imperfection shape of stiffened panels in shear has to be found by trial. Due to this reason imperfection shapes and magnitudes were studied in different stiffening models. Part 1 of this paper presents the main test results, the verification of numerical models as well as the imperfection study. In Part 2 the results of an extensive parametric study will be presented and the new design rules in prEN1993-1-5 will be tested against those results and discussed into detail.

2. Experimental work

2.1. General

The aim of four full-scale tests was to examine a characteristic behaviour of closed longitudinal stiffeners with different bending stiffness and position as well as their influence on the panel shear resistance. The test results also serve for the verification of numerical models.

2.2. Test girders

The overall test girder geometry was the same for all four tests (see Fig. 1) and it was chosen within the range of common engineering practice for bridge design. The web was slender with the ratio of $h_w/t_w = 250$. Both-sided transverse stiffeners divided each girder into three equal panels with the aspect ratio of $\alpha = a/h_w = 1.25$. With an additional pair of transverse stiffeners at both girder ends the rigid end posts were assured.

The varying parameters in the tests were the position and the stiffness of a trapezoidal longitudinal stiffener. For two girders the longitudinal stiffener was located at the web mid-height ($h_1/h_w = 1/2$), for the other two at one third of the web height measured from the upper flange ($h_1/h_w = 1/3$). For each stiffener position two different stiffeners were chosen according to preliminary numerical analysis: a weaker stiffener in order to obtain predominantly global buckling of the whole panel and a stronger stiffener in order to achieve predominantly local buckling in the sub-panels. When considering γ^* as the minimum stiffener bending stiffness of an equivalent flat stiffener, which theoretically assures pure local buckling at an elastic critical shear load, all four test girders can be determined as follows:

- **Girder 1 (G1)**: $h_1/h_w = 1/2$, weaker stiffener — $\gamma = 0.5 \cdot \gamma^*$
- **Girder 2 (G2)**: $h_1/h_w = 1/2$, stronger stiffener — $\gamma = 1 \cdot \gamma^*$
- **Girder 3 (G3)**: $h_1/h_w = 1/3$, weaker stiffener — $\gamma = 1 \cdot \gamma^*$
- **Girder 4 (G4)**: $h_1/h_w = 1/3$, stronger stiffener — $\gamma = 3 \cdot \gamma^*$.

Fig. 2 shows the exact stiffener geometry.

2.3. Material of test girders

The test girders were designed with the steel grade of S 235 according to Eurocode with a nominal yield strength of $f_y = 235$ N/mm^2. In order to obtain more accurate material characteristics for numerical simulations, three tensile tests were carried out to determine the elastic–plastic strain–stress relation for each plate thickness: a 4 mm thick plate for the longitudinal stiffeners, a 6 mm thick plate for the webs and a 25 mm thick plate for all the flanges and the transverse stiffeners. The results are summarized in Table 1, where R_{eH}, R_{eL} and R_{eS} denote the high, low and static value of the