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A NUMERICAL PARAMETRIC STUDY ON THE LOAD CARRYING BEHAVIOR UNDER BENDING OF HONEYCOMB GIRDERS

TOBIAS PETERSEN and MANUEL KRAHWINKEL

Innovative Bauweisen und Baukonstruktion, HafenCity University, Hamburg, Germany

A honeycomb girder (HCG) is defined by a mirror symmetric arrangement of two trapezoidal corrugated steel sheets (TCSS). Mechanical fasteners such as screws or rivets connect them. The high bending stiffness of HCGs provides the opportunity to span distances up to 14.0 m. Especially in the application as a cladding of roofs and facades of industrial steel-framed buildings this new construction type promises the potential to improve the resource and economic efficiency of these buildings. Former experimental investigations verified a numerical model. Based on this finite element method (FEM) model a parametric study on HCGs with an equidistant fastener arrangement has been carried out. By applying three design criteria on the numerical results the maximum characteristic surface loads for 360 HCG constellations have been determined. This paper investigates the influence of a graduated arrangement of mechanical fasteners in HCG systems on their maximum characteristic surface load.

Keywords: Cold-formed, FEM, Thin-walled, Light gauge, Simulation, Steel sheet, Graduated mechanical fasteners.

1 INTRODUCTION

In the past, trapezoidal corrugated steel sheets (TCSS) (see Figure 1) have been established as an efficient way of cladding the facades and roofs of industrial steel-framed buildings. The trapezoidal geometry of this cold-formed profile generates the stiffness, which is necessary to reach a span of up to 10.0 m. The height of these profiles has the greatest influence on the stiffness and therefore on the reachable span as well. The production process has reached a maximum with a height of up to 200 mm. Hence, it needs to find other solutions to increase the span of these profiles. A honeycomb girder (HCG) is defined by a mirror symmetric composition of two TCSSs (see Figure 1). Mechanical fasteners such as screws or rivets connect them. This connection creates a honeycomb-like profile, which permits double height and thereby explicitly improves the stiffness compared to a single TCSS. The load carrying behavior of this construction under bending is affected by the geometric nonlinear behavior of the single sheeting and the nonlinear behavior of the connection under shear.

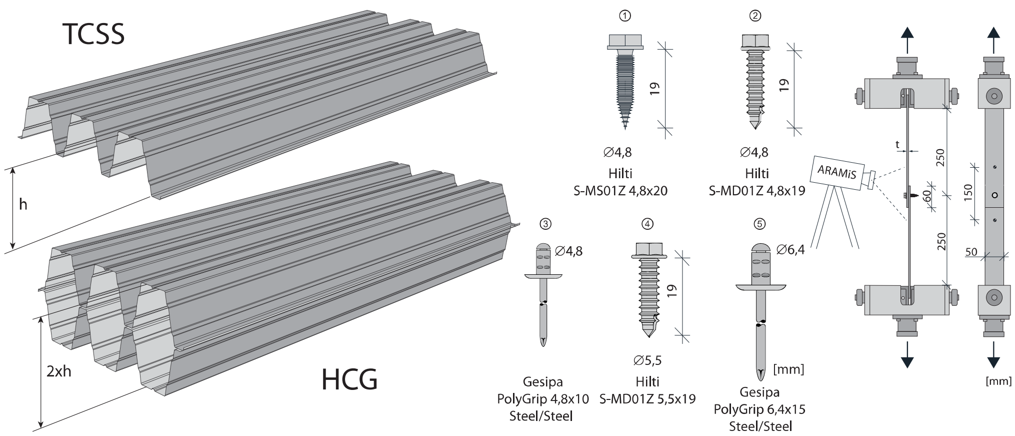

Figure 1: TCSS Type Hoesch T-150.1 - HCG made of 2 TCSSs Hoesch T-150.1- Investigated mechanical fasteners – Test setup according to ECCS (2009).

In former publications experimental investigations in line with Eurocode 3 (DIN EN 1993-1-3 2010) on the load carrying behavior of HCGs under bending were presented and a numerical model became introduced and verified by comparing its results with corresponding laboratory tests (Petersen and Krahwinkel 2014a, 2014b). Both, experimental and numerical investigations, focused on HCGs in simple beam systems. In order to describe the connection between the TCSSs in HCGs numerically with spring elements, 400 shear tests according to ECCS (2009) have been carried out in advance. For each of the five mechanical fasteners in Figure 1 the combination with 4 sheet thicknesses t_N (0.88 mm, 1.00 mm, 1.25 mm and 1.50 mm) has been investigated due to their spring characteristic. The test setup is illustrated in Figure 1. Based on these pre-investigations a fundamental numerical parametric study has been carried out in order to investigate 360 HCG constellations due their maximum characteristic surface load $q_{k,max}$. The HCG constellations differed in span distance (7, 8 ,9 ,10, 11, 12, 13, 14 and 15 m), fastener type (see Figure 1), sheet type (Hoesch T-150.1 and T-160.1) and sheet thickness t_N (0.88 mm, 1.00 mm, 1.25 mm and 1.50 mm) (Petersen and Krahwinkel 2015). In this former parametric study the fastener distance e has been chosen equidistantly constant to 333 mm. Therefore this paper investigates the influence of a graduated fastener arrangement in HCGs on their maximum surface load $q_{k,max}$ based on the numerical model used in Petersen and Krahwinkel (2015). The investigated fastener graduations behave affine to the shear force distribution of a simple beam under a uniformly distributed load. After an overview on the applied procedure to identify $q_{k,max}$ the results of the numerical investigations of this paper become presented and discussed.

2 DESIGN CRITERIA

Figure 2 shows 3 different criteria, which were used to determine the maximum characteristic surface load $q_{k,max}$ for HCG systems out of numerically simulated results. In the serviceability limit state (SLS) a maximum midspan deflection of *l/150* defines the deformation criterion (a). In the ultimate limit state (ULS) two different criteria need to be considered. Firstly the stress criterion (b), in which the maximum calculated equivalent stress $\sigma_{eq,FEM}$ of the numerical model is compared to the nominal characteristic yield strength $f_{y,k}$ and secondly the connection criterion (c), in which the calculated maximum shear force in the spring elements V_{FEM} (see Figure 2) is compared to the characteristic shear force $V_{R,k}$ of the connection taken out of the statistically evaluated shear tests, need to be kept. For each criterion all safety factors are summarized as multipliers for the FEM results. The maximum characteristic surface load $q_{k,max}$ is reached as soon as one of the criteria in Figure 3 becomes invalid.

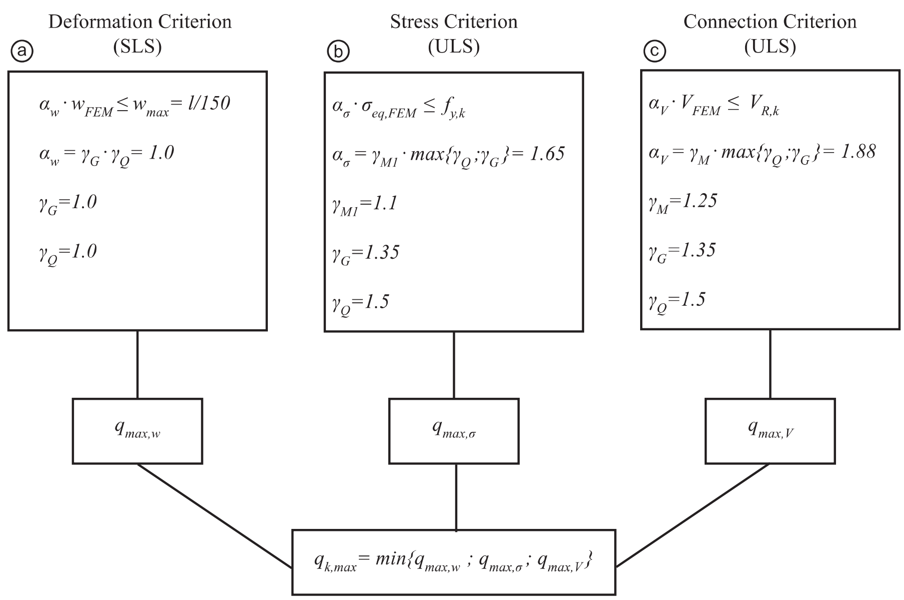

Figure 2: Design criteria for HCG constellations to determine the maximum characteristic surface load $q_{k,max}$.

3 INVESTIGATED FASTENER ARRANGEMENTS AND SYSTEMS

All investigated HCG systems in this paper consist of two Hoesch T-150.1 profiles (see Figure 1) with a nominal thickness t_N of 0.88 mm connected with Hilti S-MS01Z mechanical fasteners. The spans varied in 1.0 m steps between 9.0 m and 14.0 m. For each span four different arrangements were investigated. To define the graduated arrangements in HCGs a composite specific approach of *Kindmann* and *Stracke* (2012) has been followed. They recommend for the arrangement of stud shear connectors in composite girders a partition of the half span distance in two sectors (A and B) as shown in Figure 3. Each of the sectors becomes 50 % of the calculated required amount of stud shear connectors. The required amount n_{req} is calculated by Eq. (1).

$$n_{req} = \frac{N_{c,Rk}}{V_{R,k}} \tag{1}$$

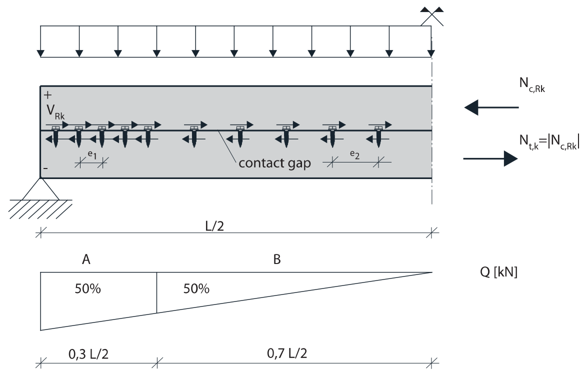

Figure 3: Distribution of the mechanical fasteners in a graduated arrangement.

where $N_{c,Rk}$ is the maximum compression force of the TCSS and V_{Rk} the statistically evaluated maximum characteristic shear force of the connection. With an amount of n_{req} mechanical fasteners the arrangement is called graduated arrangement with a calculative doweling ratio of 100 % ($\eta_{req,cal}$ = 100%). Additionally a calculative doweling ratio of 150 % ($\eta_{req,cal}$ = 150%) became investigated. Due to comparative reasons an equidistant arrangement with a mechanical fastener distance e of 333 mm as well as HCG systems with a fully bonded contact were numerically simulated. The secondly mentioned HCG systems with a fully bonded contact were set up to determine the effective doweling ratio η_{eff} for each arrangement.

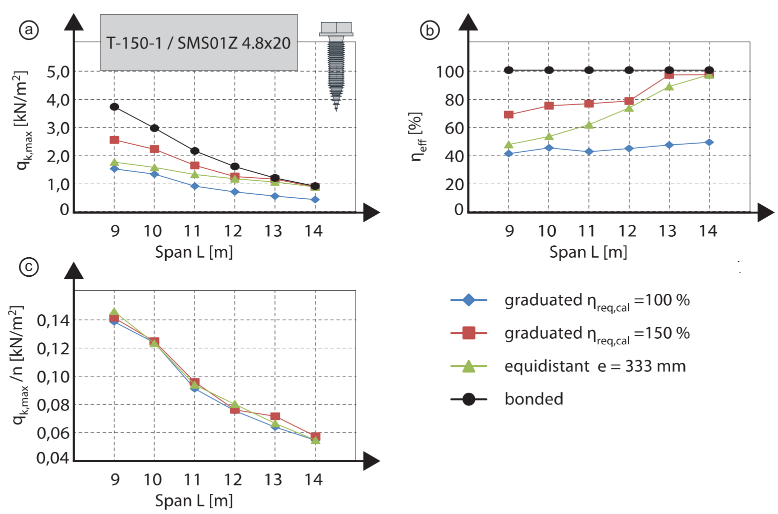

Figure 4. Results of the parametric study.

4 RESULTS

The dimensions and results for each HCG system are listed in Table 1. Figure 4 illustrates these results. As expected the highest maximum characteristic surface loads

$q_{k,max}$ were allocated by HCG systems with a fully bonded contact formulation. HCG systems with a graduated fastener arrangement and a calculative doweling ratio of 100 % generate the smallest $q_{k,max}$ values. With an increasing span the values for $q_{k,max}$ of the different arrangements and similar span equate.

Table 1. Results of the parametric study: graduated vs. equidistant arrangements.

Arrangement	L (m)	n (-)	e_1 (cm)	e_2 (cm)	Cr (-)	$q_{k,max}$ (kN/m²)	η_{eff} (-)	$q_{k,max}$ / n (kN/m²)
graduated $\eta_{req,cal}$ = 100 %	9	13	19,3	52,5	b	1,538	0,414	0,118
	10	13	21,5	58,3	b	1,348	0,454	0,104
	11	13	23,6	64,2	b	0,928	0,428	0,071
	12	13	25,8	70	b	0,728	0,450	0,056
	13	13	27,9	75,8	b	0,578	0,475	0,044
	14	13	30	81,7	b	0,458	0,494	0,035
graduated $\eta_{req,cal}$ = 150 %	9	20	13,5	31,5	b	2,558	0,688	0,128
	10	20	15	35	b	2,228	0,751	0,111
	11	20	16,5	38,5	b	1,658	0,765	0,083
	12	20	18	42	b	1,268	0,784	0,063
	13	20	19,5	45,5	a	1,178	0,967	0,059
	14	20	21	49	a	0,898	0,968	0,045
equidistant 333 mm	9	14	33,3	33,3	b	1,778	0,478	0,127
	10	15	33,3	33,3	b	1,588	0,535	0,106
	11	17	33,3	33,3	b	1,338	0,617	0,079
	12	18	33,3	33,3	b	1,188	0,734	0,066
	13	20	33,3	33,3	b	1,078	0,885	0,054
	14	21	33,3	33,3	a	0,898	0,968	0,043
bonded	9				c	3,718	1,000	
	10				c	2,968	1,000	
	11				a	2,168	1,000	
	12				a	1,618	1,000	
	13				a	1,218	1,000	
	14				a	0,928	1,000	

Cr = Criterion a, b, c see figure 2 $\eta_{eff} = \frac{q_{k,max}}{q_{k,\max(bonded)}}$ $\eta_{req,cal} = \frac{n}{n_{req}}$

Figure 5 illustrates the distribution of the shear forces $V_{Spring,d}$ in the connections of HCGs readout from the nonlinear spring elements in the numerical simulation. The plotted distribution belongs to the loadstep on which the first of the criteria in section 2 becomes invalid. For an equidistant arrangement the maximum shear force occurs in connections close the support areas. For graduated arrangements the maximum shear force is located in the sector B (see Figure 5) near the transition zone to sector A. This local maximum is responsible for the low values of the maximum characteristic surface load $q_{k,max}$ of HCGs with graduated arranged mechanical fasteners.

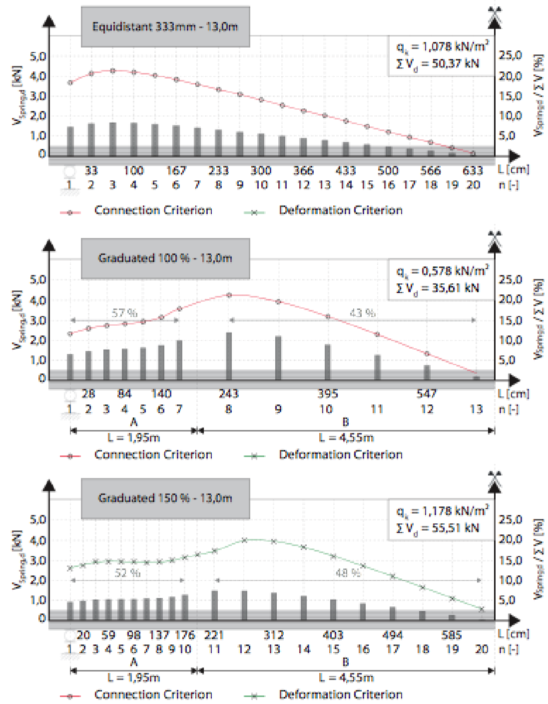

Figure 5. Distribution of the shear forces in the connection when reaching $q_{k,max}$.

5 CONCLUSIONS

By comparing the effective doweling ratios for the 13.0 m HCG system with a graduated fastener arrangement and a calculative doweling ratio of 150 % (η_{eff}=96.7%) with the 13.0 m HCG system with an equidistant fastener arrangement (η_{eff}=88.5%), both with 20 fasteners per half span and wave, the influence on load bearing capacity of a fastener graduation can be evaluated (see Figure 4). The difference of 8.2 % seems not legitimate higher erection complexity of the fastener graduation in practice.

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