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Design of slip resistant lap joints with long open slotted holes

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ABSTRACT

Current design procedures for slip resistant connections according to Eurocodes and American specifications are reviewed. Although failure of a slip resistant connection is defined at different levels of slip, 0.15 mm and 0.5 mm respectively, the calculation of the resistance is similar. Most of the research is performed on bolts in normal clearance holes. A testing program was conceived to evaluate the influence of long open slotted holes on the behavior of slip resistant lap joints with tension control bolts because of possible use of such connections in towers for wind turbines. In comparison to specimens with normal clearance holes it is found that the friction coefficient is about 4% lower. This reduction is lower than suggested by the current correction factors. Since none of the design procedures takes the reduction in bolt forces by time into account, the loss of pretension force is experimentally studied and an approximation is proposed. A second testing program was carried out with friction standard specimens in order to determine the slip factor for different surface treatments and steel grades in range between S275 and S690. The achieved slip factors for different surface preparations are in accordance with the classification of friction surfaces in EN 1090-2:2008 and differences obtained are addressed to variations in exposure to weather conditions. The steel grade does not have a significant influence.

1. Introduction

Slip resistant connections assume no slip at the ultimate limit state and therefore they are advantageous for many applications of bolted connections loaded in shear. Such connections are suitable for alternating loads. The fatigue detail category is 112 for a butt joint and 90 for a lap joint compared to the corresponding detail category of 50 for butt and lap joint connections with non-pretensioned bolts in normal clearance holes [1].

Control of the initial pretension force in the bolts and the remaining force during the lifetime of the connection, in addition to the friction coefficient of the joined surfaces, are the main parameters for safe slip resistant connections. Two methods exist to introduce a pretension force: either by applying a torque moment or a tensile force. However, the nominal hole clearances impose rather tight tolerances which are an important issue for fast assembly. An innovative assembling connection in tubular towers for wind turbines is investigated in a project named HISTWIN, where the use of long open slotted holes, as they can be seen in Fig. 1, is thoroughly studied [2]. The term "long open slotted hole" describes a hole with geometry of a long slot, which is open at one end to ease and quicken the construction. European and American design codes allow the use of oversized and slotted holes to simplify erection. However, the design resistances need to be reduced accordingly. To avoid the development of corrosion, the surfaces of the steel components must be protected. The surfaces are blasted with shot or grit with loose rust removed, followed by a spray-metalized with an aluminum or zinc based product or rather often with an alkali–zinc silicate paint. Different types of surface treatments lead to different values for slip factors. The surface classification and corresponding slip factors are well established, see Table 1, for steel grades up to S460, according to EN1993-1-8 [3].

In this paper, the current design procedures according to Eurocodes and American specifications are reviewed and the background for their recommendations is provided. Results of the standard test for slip factor performed for different surfaces and results of experiments of lap joints coated with ethyl silicate zinc rich paint and assembled with Tension Control Bolts (TCB) are presented. The effects of long open slotted holes and friction properties on the bolt forces are investigated in static and long term tests. Finally design recommendations are given. A characteristic resistance function of the lap joint with long opened slotted holes for a period of 20 years is extrapolated based on the long term tests.

2. Design procedures

The format of the design procedure used in Eurocodes and American specifications for slip resistant connection with oversized and slotted holes is shown below.

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Notations

D	slip probability factor
$F_{p,C}$	preloading force
$F_{S,average}$	average test value of the slip force
$F_{S,min}$	minimum test value of the slip force
$F_{S,max}$	maximum test value of the slip force
$F_{S,Rd}$	design slip resistance
R_S	service-load slip resistance
T_m	specified minimum bolt pretension
V	variation coefficient
$\underline{X}_m$	array of mean values of the basic variables
$g_{rt}(\underline{X})$	resistance function (of the basic variables $\underline{X}$) used as the design model
k_s	correction factor for different hole geometries
n	number of friction surfaces
r_t	theoretical resistance determined from the resistance function $g_{rt}(\underline{X})$
r_d	design resistance
s_μ	standard deviation
α_R	First Order Reliability Method sensitivity factor for resistance
β	reliability index
γ_{M3}, γ_M	partial safety factors
μ	slip factor (EN 1993-1-8) or friction coefficient (RCSC)
μ_{char}	characteristic value of the slip factor
μ_m	mean value of the slip factor
$\mu_{proposed}$	proposed value of the slip factor
Φ	resistance factor (RCSC) for different hole geometries

2.1. Design procedure acc. to EN1993-1-8

The design slip resistance of a connection with a single preloaded high strength bolt is given in EN1993-1-8 [3] as:

$$F_{S,Rd} = \frac{k_s\, n\mu}{\gamma_{M3}} F_{p,C} \tag{1}$$

where n is the number of faying surfaces. The slip factor μ is taken in accordance with EN1090-2 [4]. Four friction classes are defined there, cp. Table 1, and the slip factor is given for the corresponding surface treatments. Alternatively, it can be obtained from specific tests, with specimens defined in EN 1090-2 [4] and using the evaluation procedure provided in EN1990 [5]. If oversized or slotted holes are used, the resistance must be reduced by applying a correction factor, k_s. Values for this are given in Table 2 for different geometries. The related clearance definitions are shown in Table 3. The bolt pretension $F_{p,C}$ is taken as 70% of the ultimate strength of its tensile stress area. For a slip resistant connection at Ultimate Limit State a partial safety factor of $\gamma_{M3} = 1.25$ is recommended. The ultimate slip state is defined as the force obtained at a slip of 0.15 mm.

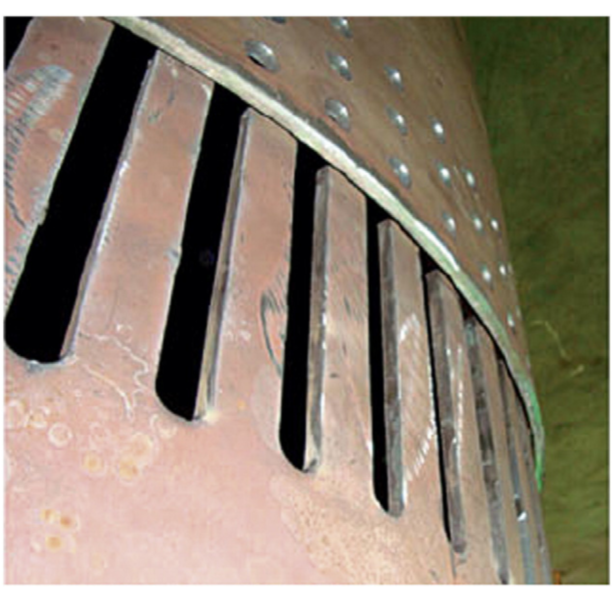

Fig. 1. Long open slotted hole [2].

2.2. Comparison with RCSC specifications

The resistance at the Service Load Level according to the *Research Council on Structural Connections* (RCSC) [6] for the *American Institute of Steel Construction* [7] is similarly given as:

$$R_n = \mu D T_m N_b \cdot \left(1 - \frac{T}{D T_m N_b}\right). \tag{2}$$

Here, T accounts for an applied tensile load, which is equal to zero if the joint itself is exposed to shear only. In case of a single bolt, where the number of bolts, N_b, then is equal to one, loaded in pure shear this equation can be simplified to

$$R_n = \mu D T_m. \tag{3}$$

The mean slip coefficient μ is taken from the corresponding surface classes, cp. Table 4. The values are similar to those given in Eurocode for uncoated clean mill scale and blast-cleaned surfaces. The friction properties have to be defined by standardized testing and must not exceed 0.50. The slip coefficient of hot-dip galvanized surfaces is reduced to 0.35 in the 1994 edition and is now lower than the value given in Eurocode.

To calculate the design resistance, R_n has to be multiplied by a resistance factor Φ, which takes the effect of hole geometry into account and is comparable to the correction factor k_s in Eurocode. The nominal clearances for normal holes, cp. Table 5, are independent of the bolt diameter and thus stricter for large bolts. The definitions of oversized and slotted holes are however very similar in both standards. Small differences can be attributed to convenience from the use of different units. Four categories are considered in the American code. Short slotted holes have the same correction as oversized holes, cp. Table 6. The recommendations from RCSC are thus more generous for short slotted holes with an axis parallel to load transfer by not reducing the resistance as much as recommended by EN1993-1-8 [3]. On the other hand they are more conservative in the case of long slotted holes parallel to load transfer. The specified minimum bolt pretension T_m is also taken as 70% of the minimum tensile strength. The slip probability factor $D = 0.8$ is equal to the inverse of the partial safety factor γ_{M3} in Eurocode. However, the ultimate slip state is defined as the force obtained at a slip of 0.5 mm [6] which may lead to higher resistance than according to the criterion used in EN1090-2 [4].

2.3. Background of the recommendations

The specifications from RCSC with regard to oversized and slotted holes are derived from the design recommendations of the *Guide to Design Criteria for Bolted and Riveted Joints* [8]. These are based on few experimental studies [9–11] where the effects of different hole clearances on the initial bolt pretension, relaxation and slip factor are investigated and accounted for in the correction factors, k_s. It should be noted from these studies that larger holes reduce the stiffness of the clamping package and larger local deformations occur.