On the behavior of headed fastenings between steel and concrete

J. Bujňák\textsuperscript{a,*} and B. Robriquet\textsuperscript{b}

\textsuperscript{a}Peikko Group, Hlinská 40, 011 18, Žilina, Slovakia
\textsuperscript{b}Polytech Clermont-Ferrand, 63174 Aubière cedex, France

Abstract

The combination of materials with different structural properties (i.e. steel and concrete) is one of the most effective ways how to improve the efficiency of building structures. The proper design and detailing of connections between structural elements made of these two materials is an essential condition for an efficient functioning of the composite structure.

The technical specification CEN/TS 1992-4-2:2009 defines design rules for headed fastenings under tensile and shear loads. A critical review of some of the design concepts included in this technical specification will be presented in the paper on the basis of experimental results. A new design concept proposed within the European project Infaso will also be evaluated.

© 2012 Published by Elsevier Ltd. Selection and review under responsibility of University of Žilina, FCE, Slovakia.

Keywords: Headed fastenings, supplementary reinforcement

1. Introduction

The proper design, detailing and execution of joints are some of the essential pre-conditions for a safe and effective functioning of building structures. In concrete or composite buildings, one of the most challenging tasks is to develop tension or moment resisting structural joints. Headed fastenings (made of ribbed or smooth steel) are a very efficient technique for such application, since they enable to anchor relatively high tensile forces while being more compact than other available systems. This is mainly due to the fact that the transfer of loads from the fastener to the concrete is localized over the contact surface between the head of the fastening and the concrete. The maximum load that might be transferred by such system thus depends principally on the dimension of the head of the fastening and not on its development length as it is the case for straight or hooked ribbed bars. At the same time, the localized transfer of loads induces in concrete high local stresses making it susceptible to premature failure by separation of a concrete cone. Such failure of the fastening may be critical...
especially for cases when the fastening is located close to the edge of the concrete member. The current experience shows that such failure may be prevented using supplementary reinforcement in the concrete member that is designed and detailed in order to tie the potential breakaway cone to the rest of the concrete body. The design approach for supplementary reinforcement against concrete cone failure of headed fastenings of the technical specification [1] that is nowadays used as reference for the development of European technical approvals has been recently discussed and criticized in [7], [8]. A new design approach for predicting the resistance of headed fastenings with supplementary reinforcement has been recently formulated within the final report of the RFCS European project Infaso [4]. This design models of reference [1] and [4] will be discussed on the basis of test results.

2. Failure modes of headed fastenings

Within the framework of the Eurocodes (see paragraph 2.7 of [2]) the design of headed fastenings is regulated by the technical specification [1] that defines a set of verifications for different failure modes of headed fasteners loaded in tension and shear. For short fasteners (with embedment length around 80-150mm), the decisive failure mode that governs the tensile resistance of the whole anchorage system is often the concrete cone failure. The characteristic resistance of a headed fastening against the concrete cone failure is defined as:

\[ N_{Rk,c}^0 = k_{cr} \cdot \sqrt{f_{ck,cube}} \cdot h_{ef}^{1.5} \]  \hspace{1cm} (1)

Exhaustive information about the background of this design concept is available in reference [6]. In the case when the fastening is adjacent to edges of the concrete member, the concrete cone failure is determined as:

\[ N_{Rk,c} = N_{Rk,c}^0 \cdot \frac{A_{c,N}}{A_{c,N}^0} \]  \hspace{1cm} (2)

where

\[ A_{c,N}^0 = 9 \cdot h_{ef}^2 \] is the reference area

\[ A_{c,N} \] is the actual area of the concrete cone (see [1]).

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_{cr} )</td>
<td>factor to represent cracks in concrete</td>
</tr>
<tr>
<td>( f_{ck,cube} )</td>
<td>cubic compressive strength of concrete</td>
</tr>
<tr>
<td>( h_{ef} )</td>
<td>effective depth of the fastening in concrete</td>
</tr>
<tr>
<td>( l_1 )</td>
<td>anchorage length of the supplementary reinforcement in the concrete cone</td>
</tr>
<tr>
<td>( d_s )</td>
<td>diameter of the supplementary reinforcement</td>
</tr>
<tr>
<td>( f_{bd} )</td>
<td>design bond strength</td>
</tr>
</tbody>
</table>
According to current experience, it is possible to increase the resistance of the fastening against concrete cone failure by using supplementary steel reinforcement. A typical arrangement of a headed fastening with supplementary reinforcement that is in accordance with the detailing rules of fib [3] is shown on Figure 1.

![Diagram of headed fastening with supplementary reinforcement](image)

Fig. 1 Typical arrangement of a headed fastening with supplementary reinforcement

The technical specification [1] defines the design value of resistance of a fastening with supplementary reinforcement as follows:

\[
N_{Rd,a} = \sum_{n} \frac{l_{1} \cdot \pi \cdot d_{s} \cdot f_{bd}}{\alpha}
\]

where \(\alpha = 0.7\) if supplementary reinforcement is bended in the concrete cone.

The fact that the approach of reference [1] for the design of supplementary reinforcement is conservative and does not predict the correct failure modes of certain types of supplementary reinforcement has been demonstrated by Fromknecht [8] who tested a series of fastening plates with headed fastenings. In all tested cases, the failure of the system happened either by pull-out of the studs from between the supplementary reinforcement or by side blow-out failure. The design values of resistance of the fastening plates determined experimentally were about 3 to 10 times higher than the resistances predicted according to [1].

A new mechanical model to predict the resistance of headed fastenings with supplementary reinforcement has been proposed within the project Infaso [4]. The resistance of headed fastenings with supplementary reinforcement is formulated as:

\[
N_{u2} = N_{sba} + \delta_{sba} \cdot k_{c} + N_{uc} \leq N_{u,max}
\]

where \(N_{sba}\) is equivalent to \(N_{Rd,a}\) determined in accordance with Equation (2) but using influence factor \(\alpha = 0.49\) and \(N_{uc}\) is equivalent to \(N_{Rk,c}\) determined by Equation (1). The symbol \(\delta_{sba}\) represents the deformation and \(k_{c}\) the axial stiffness of the stirrups in tension (see reference [4]).

The maximum value of resistance is limited by the crushing of concrete in the concrete strut between the headed fastening and the supplementary reinforcement and is determined as:
The factor $\Psi_{\text{support}}$ takes account of the shape of the failure cone of concrete characterized by distance $x$ between the fastening and the edge of failure surface (see [4]):

$$\Psi_{\text{support}} = 2,5 - \frac{x}{h_{\text{ef}}} \geq 1$$  \hspace{1cm} (6)

3. Experimental analysis

A series of simple tensile tests have been performed at the University of Zilina in Slovakia in 2011 to demonstrate the failure modes of short headed fastenings with supplementary reinforcement. Detailed information about the test procedure and results may be found in reference [5].

The test specimens consisted of a headed stud (diameter 16mm) cast into a concrete cube of size 200x200x200 (Figure 2). The headed studs were surrounded with two U-shaped bars (diameter 10mm) that have been used to represent the effect of supplementary reinforcement against concrete cone failure of the headed fastening. The U-shaped bars were welded to a back anchor plate. Three other steel plates (non-hatched on Figure 3) had no load bearing function; they have been used to create a casting box for concrete. The two side plates have been mechanically removed after hardening of concrete.

![Fig. 2 Geometry of the test specimens](image)

The anchorage length of U-shaped bars inside of the concrete cone is $l_1=50$mm. The ratio $l_1/d_s = 5$ is thus higher than the minimal value required by CEN/TS 1992-4-2:2009 [1] (min. $l_1/d_s = 4$). The axial distance of the U-shaped bars in test series PST-13 was 30mm so that they enclose the head of the stud (Figure 4). A transverse stirrup with diameter 6mm was used to provide confinement to the concrete between the U-shaped bars and the headed stud (Figure 2).

The headed studs as well as the U-shaped bars were made of steel B500B with material properties in accordance with [2]. The cubic compressive strength of concrete was $f_{\text{ck,cube}}=31,1$MPa.

The test arrangement is illustrated on Figure 3. The test specimens have been fixed into a testing frame and tensile force was applied to the headed stud using a universal tensile machine of type Matest H011. The specimens were continuously loaded at rate 0,5 kN/s until failure. The load displacement behavior of the test
specimens was continuously recorded with two displacement gauges fixed on two opposite sides of the specimens.

![Fig. 3 Test arrangement](image)

The load displacement curves of test specimen PST-13.1 and PST-13.2 are shown on Figure 4 a). Both testes specimens failed by crushing of concrete between the headed stud and the supplementary reinforcement.

![Fig. 4 a) Load-displacement curves of the tested specimens](image)  
![Fig. 4 b) Evaluation of test results](image)

4. Discussion

Figure 4 b) compares the design values of resistances of test samples to resistances determined in accordance with [1] and the new design model proposed within the project Infaso [4].

The experimentally determined design values of resistances are calculated as:
with γc=1.5 and \( N_{ult} \) is the maximum load reached in the tests. The design value of resistance against anchorage failure of supplementary reinforcement is determined using Equation 3 considering concrete class C30/37 with good bond conditions.

The design concept for resistance of headed fastenings with supplementary reinforcement used in the technical specification [1] and included into the recently published fib Bulletin No 58 [3] does not predict the correct failure mode of specimens tested within the experimental program presented in this paper. It also severely underestimates the resistances of fastenings with parameters similar to those of the fastening tested within the experimental program presented in this paper.

The new design approach proposed within the project Infaso [4] predicts the correct failure mode of the tested specimens (failure of the concrete strut). Within this design model, the resistance of the concrete strut is determined as a function of the resistance against concrete cone failure. Two possible applications of this formulae are evaluated within this study:

\[
N_{u,max}^1 = \psi_{support} \cdot N_{Rd,c}^0 \\
N_{u,max}^2 = \psi_{support} \cdot N_{Rd,c}^0
\]  

The comparison on Figure 4 b) shows that the resistance of the concrete strut determined on the basis of the maximum resistance against concrete cone failure correlates with the experimentally determined values of resistance. The design value of resistance determined using the concrete cone failure resistance reduced due to the presence of edges in concrete seems to severely underestimate the experimentally determined resistances.

5. Conclusions

The fact that the current technical specification [1] does not predict the correct failure mode and underestimates the resistance of short headed fastenings with a specific arrangement of supplementary reinforcement has been demonstrated on the basis of results of experimental analysis. The new design concept proposed within the project Infaso [4] seems to predict the correct failure mode of the tested system. At the same time, a revision of the model in order to integrate the effect of concrete edges located adjacent to the fastening seems necessary.

References