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Bearing strength of shear connections for tubular structures: An analytical approach

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ABSTRACT

This work deals with the prediction of the bearing resistance of elementary shear connections constituted by gusset plates and square hollow sections fastened with long bolts. The research is motivated by the lack of specific rules in international codes for this particular configuration. In fact, while in lap shear connections, single or double-sided, the holes are always confined out of plane, in case of connections with long bolts and gusset plates (typical of tubular structures), the holes are constrained out of plane outwards, but they are free to buckle inwards, providing a reduction of the bearing strength. Within this framework, the paper is aimed at the development of an analytical formulation for the prediction of the bearing resistance of connections with long bolts and square hollow sections (SHS). The proposal is based on the calculation of the post-buckling load of the tube plate subjected to bearing at the bolt hole, combining the Winter's formula (originally developed to predict the post-buckling strength of steel plates accounting for geometrical and mechanical imperfections) with a simplified FE model developed in SAP 2000. The procedure developed is presented in detail proposing a design equation for connections with long bolts, based on a formula suggested recently by Može (2014, 2016) suitable for the inclusion in code provisions such as EC3. The accuracy of the design equation is checked on the experimental data reported in a previous work of the same authors properly extended with parametric FE simulations to cope for variation of geometrical parameters.

1. Introduction

Bolted connections are widely used in steelwork because they are easy to manufacture while providing significant benefits in terms of constructability [48,49]. In fact, they allow to split complex structures in simpler parts which can be welded in the shop (assuring a high quality of welds) and bolted on the construction site. Almost all bolted connections, in order to provide an appropriate response, need to activate the typical mechanisms for the transfer of shear forces, thus requiring to check resistance accounting for different possible failure modes. In the most elementary type of connections, plates are simply overlapped according to single-sided or double-sided lap shear configurations, providing the load transfer through the activation of bearing stresses and shear forces in plate and bolt. The bearing stresses develop in the area of the plate ahead of the bolt shank and, usually, due to a combination of material strain hardening and stress triaxiality, they achieve levels much beyond the yield limit of steel [1–3,50,51]. In order to account for this triaxial stress state, promoted by the lateral confinement of the bolt head or nut, currently, all the national and international codes suggest to adopt an average value of the bearing stress which can achieve, depending on the level of confinement, up to four times the ultimate resistance (f_u) of the base material [4–6].

In case of classical double-sided and single-sided lap shear connections, the bearing strength has been extensively investigated over the last twenty years both for standard and Cold-Formed Steelwork (CFS). However, if reference is made, as an example, to the European (Eurocode 3 part 1.8 [4] and Eurocode 3 part 1.3 [5]) and North-American design codes (AISC 360-10 [7] and AISI S100 [6]), many differences, mainly related to the background documentation followed to develop the standardized design procedures can be still recognized. Generally, it is common practice to merge in the same formula the checks for the so-called bearing and tear-out failure modes, expressing the bearing resistance at the bolt hole as the product of an average bearing stress multiplied by the bearing area. However, even though the equation is expressed in this way in all the most widespread standards, the definition of the design bearing factors does not find a common agreement. As an example, in AISI S100 the bearing stress may range, in case of standard holes, from $1.35f_u$ (for very thin plates and

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minimum confinement) to $4f_u$ (for thick plates and maximum confinement). Differently, but with a similar equation, AISC 360-10 limits the average bearing stress to an upper bound value of $3f_u$. Conversely, in European practice, Eurocode 3 part 1.8 limits the bearing factor to a maximum value equal to $2.5f_u$ being, therefore, much more conservative than all the other design provisions. This lack of consistence between the various design provisions has already been evidenced by several authors (e.g. [2,8,9]). Though, the definition of a unique and commonly accepted criterion is still far from being achieved. In the European framework, the most recent proposals are those provided by the research group of the University of Ljubljana that, in a series of works published since 2010 [1–3], has suggested a more accurate procedure for the European practice, developing a new equation validated on a large set of experiments including mild and high strength steels. This new formula considers the possibility to achieve an average bearing stress equal to $3f_u$, limited, eventually, by the development of tear-out failure modes, which are accounted for with an approach similar to the one reported in the earlier versions of the AISC specification (1993) [9,10]. Examples of other recent works, which underline the continuous need for more accurate design procedures, as well as the complexity of the topic, are those of Salih et al. [11], Kim & Kuwamura [12] and Kymaz [13] regarding the behaviour of bearing in stainless steel connections, Draganić et al. [8] or Teh & Uz [14] dealing with single sided connections, the series of works by Teh and coauthors [14–17] or other recent experimental works [18–24].

As herein described, the technical literature regarding the bearing resistance at bolt holes is very wide. However, it is practically exclusively devoted to sheet-to-sheet connections in double-sided or single-sided configurations, neglecting other possible configurations, such as the case of connections with long bolts fastening structural elements with a gap (e.g. hollow sections, channels or simply spaced gusset plates). Nevertheless, even in absence of regulations and specific experimental works, such a kind of connections are widely used in constructions, in CFS assemblies and ordinary steelwork, for trusses, racking systems, bracings, scaffoldings, etc. (Fig. 1). Indeed, at the authors best knowledge, currently the only explicit specification in design standards for this connection typology is that reported in AISC 360–10 [7] (Equation J7-1), while there are only very few theoretical and experimental works, such as that of Yu & Panyanouvong [25].

The main difference between a traditional sheet-to-sheet connection and a connection with long bolts passing completely through the member is that due to the lack of installation space, the bolt head or nut can confine the plates subjected to bearing only outwards, while inwards they are free to buckle (Fig. 2). Clearly, compared to the classical overlapped configurations, this leads to a strong decrease of the confinement, thus reducing the value of the maximum achievable bearing stress. In fact, as already evidenced in [26], in many cases, in this type of connection, due to the development of a particular out-of-plane failure mode of the plate, the bearing stresses cannot attain values as high as those reported neither in the recent proposal of Može [3] (i.e. $3f_u$) nor in the AISI S100 or EC3 provisions (i.e. $2.25f_u$ [26] or $2.5f_u$ [4,5]).

Within this framework, aiming to provide a contribution towards the development of specific design guidelines for connections composed by gusset plates, squared hollow sections and long bolts, the main goal of this paper is to investigate the behaviour of this joint typology, suggesting an analytical formula able to predict the bearing strength at bolt holes. This is made introducing in the recent proposal for revision of Eurocode 3 of Može et al. [2,3] a further check to be considered only in case of connections with long bolts and Squared Hollow Sections (SHS). The new analytical formulation is based on the calculation of the post-buckling load of the tube plate subjected to the bearing action of the bolt, combining the Winter's equation [27] (originally developed to predict the post-buckling strength of steel plates under compression, accounting for geometrical and mechanical imperfections) with a simplified FE model developed in SAP 2000 [28]. This model is used to determine the elastic buckling load for the particular loading condition (patch load with partial rigidity constraints) which, otherwise, would be quite complex in a closed form. The procedure developed is presented in detail proposing a design equation whose accuracy is checked on the experimental data reported in a previous work of the same authors properly extended with parametric FE simulations [26]. The additional FE analyses are carried out in order to consider the variation of the main geometrical parameters influencing the bearing resistance.

2. Current design practice for bearing strength at bolt holes

In order to provide a state of the art on the current practice for the bearing strength at bolt holes, in the following the main suggestions available in design standards are summarized.

The AISI S100 code is essentially based on the works of Yu, Zadanfarrokh and Bryan, LaBoube and Yu, Wallace, Schuster and LaBoube and Rogers & Hancock [29–41]. In particular, Rogers & Hancock first and Wallace, Schuster and LaBoube after, conducted tests on CFS bolted connections defining, as it is made in all the codes, the bearing strength as dependent on the tensile strength of the plate (f_u), thickness of the sheet (t) and bolt diameter (d). Additionally, the authors after verification with a database including various research reports, expressed the stress bearing coefficient as the product of a modification factor m_f, multiplied by a bearing factor C dependent, in turn, on the t/d ratio. The product of these two coefficients may lead, for connections with standard holes, to values of the bearing stress ranging from a minimum of $1.35f_u$ ($d/t > 22$, single-sided or outside sheet of a double shear connection without washers or only one washer)

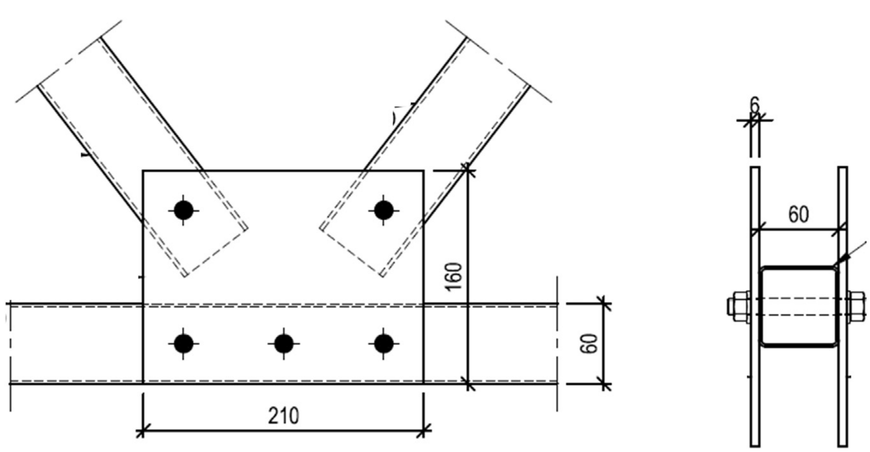

Fig. 1. Example of a typical configuration of a joint with tubular elements, gusset plates and long bolts.