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# Strain measurements and analyses around the bolt holes of structural steel plate connections using full-field measurements

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ABSTRACT

The mechanical response of cover-plates connections combines various phenomena such as the contact evolution between bolts and holes, the elastic-plastic behavior of the constitutive materials and the effect of large displacements occurring in some cases. The interaction between the holes in the plates needs to be evaluated regarding various configurations of joint and hole positions, especially to take into account the localization of failure around bolts. The different failure modes such as net section fracture, gross section yielding, shear out and bearing, are difficult to predict because they combine local compression under bolt and shear at loaded end distance of the plate. Numerical models show the complexity of stress distribution around the holes depending on the connection configurations. The main originality of this work is to rely on a full-field measurement technique, namely the grid method, to estimate the strain fields that really occur in the specimens under test. Compared to digital image correlation, this technique features a better compromise between strain resolution and spatial resolution. This enables us to analyze in details the strain distribution on the plates with various configurations for the bolts and holes. Both the elastic and the plastic regimes are analyzed. This approach enables us to understand the evolution of the failure zones regarding the bearing mode. A numerical simulation is finally performed and obtained results are compared with their experimental counterparts. Differences observed highlight the relevance of full-field measurements in the current context of high strain gradients.



## 1. Introduction

In steel structures, bolted joints are commonly used in combination or not with welded parts. For practical reasons, bolted connections are mainly used because they allow a quick and easy building process on site. Cover-plate types combine plates, gussets, flanges or webs with bolts subjected to shear. These connections allow transferring various types of internal forces between elements such as bending, shear or tension and compression [1]. Generally, joints are singular discontinuities as they ensure the transmission of forces between elements through components of limited dimensions. The knowledge of basic cover-plate behavior can be generalized to a wide variety of joint configurations supporting normal and shear forces, with or without bending moments. Even in usual simple configurations, the global load-displacement behavior of cover-plate joints involves complex pattern of deformations in gross cross-section, net cross-section, bolts in shear and bearing zone under the bolts [2,3]. The mechanical response of cover-plates connections combines various phenomena such as the contact evolution between bolts and holes, the elastic-plastic behavior of the constitutive materials and the effect of large displacements occurring in some cases. In the joints with more than two bolts, the load distribution among bolts, depending on the joint configurations and hole positions, need to be evaluated to take into account the localization of failure around bolts. This is mainly true for materials with low ductility. Besides, for materials featuring large ductility such as austenitic stainless steel, the deformation of the connection around the bolts needs to be limited at the serviceability limit state [4–6]. In all cases, the failure modes observed in the connections can be classified in various families (net section, gross section, bearing and bolt-shear).

Many studies analyzed the behavior of cover-plate joints in structural elements such as braces, flanges and webs continuities, angles and tubes considering carbon steel or aluminum and stain-

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less steel. Bearing failure can be combined with block shear mechanism in coped beams for which a limited number of studies and tests are realized to check the validity of analytical formulae used for designing purposes [7,8]. The tests can help understand the real behavior of the connections, to evaluate the resistance of the connection and to observe the failure mode. They are generally used to validate numerical and analytical models. In the tests which are commonly carried out, measurements used are in general global displacement combined with some local strain gauges. In joints containing several bolts, the failure mode associating block-shear and net section in gusset plates is common. Finite element models are generally developed and validated on experimental results to understand and predict this complex failure mode [9]. In thin-walled elements, the ultimate strength of the bolted joint can be significantly reduced by the curling effect in long-end distances due to the instability of the compressed zone. This is confirmed by tests and FE models with changing end distances, edge distances and plate thicknesses [10].

Several studies were undertaken to take into account the large deformation induced by the behavior of the stainless steel connections regarding the stiffness, the strength and the deformation capability [4,6]. Some applications concerned the austenitic and ferritic stainless steels, with the development of 3D finite element numerical models for connections failing by net section fracture. The numerical deformation around the bolts and the edge distance [5]. Similar analysis was performed on stainless steel connections failed due to bearing with representation of the distribution of plastic deformations in different zones under the bolt at the end distance zone and deformed shapes [6]. The numerical models showed the complexity of stress distribution around the bolts depending on the connection configurations. This concerns mainly the zone affected by the bearing failure which is defined by the end distance in the direction parallel to the loads. The models and tests are used to develop or check the design formulae which are similar between carbon steel and stainless steel with some adaptations. Analytical equations used for design purposes are generally compared to experimental results for various configurations of joints to check their ability to define the ultimate shear-out capacity of steel bolted connections for structural applications. The equations used in Eurocode 3 [11] to check the strength of steel joints regarding the bearing failure mode combine various phenomena (shear-out or tear-out and bearing).

Besides, many available studies were developed to take into account the real joint characteristics to be included in the global analysis of structures. Thus, cover-plates can be considered as a basic component of connections. They are used to identify a moment-rotation law for various configurations of connections [12]. Bearing failure modes can also be observed in plate connections on circular hollow steel sections with more complex loading and behavior [13] or in thin steel plate shear walls attached to boundary frame members [14]. The bearing failure modes combined to curling due to the thickness of the steel sheets need to be carefully analyzed to reach optimal structural performance of cold-formed steel connections [15].

Usual factors involved in the complex behavior of bolted connections come from the material, the dimensions of the plate and the relative position of the holes. For joints with slender bolts or thin elements, out-of-plane displacements of the plates [16] and bending of the bolts need to be considered in the corresponding models. In the present study, bolts are considered with low slenderness. They are associated with plates with sufficient thickness. Thus, the out-of-plane bending displacements of the plate (curling) and its effects can be neglected.

The use of full-field measurement systems to characterize the mechanical response of bolted joints remains scarce in the literature [17]. This leads to an underuse of powerful measuring tools in structural testing despite their evident benefit to assessing the real strain distribution that occur in the case of strong strain gradients or concentrations. In the present study, the grid method is used to analyze in details the strain distribution on the plates with various configurations of bolts and holes positions. As pointed out in [18], this technique features a good compromise between measurement resolution and spatial resolution. The first quantity is the smallest reliable strain that emerges from the noise floor. The second one reflects the ability of the technique to distinguish close features in a strain field.

This technique was recently successfully employed in cases for which high strain gradients had to be detected and measured [19–21], especially in civil engineering applications. For instance the strain field in early and late woods was measured in wooden beam in [22], while localized strain peaks could be detected in various asphalt specimens in [23]. The compromise between strain and spatial resolutions is globally better than that achieved with subset-based digital image correlation [24], which led the authors to use the grid method in the present study.

As a general remark, full-field measurements enable us to observe the strain fields in the plate around the bolts in the elastic and plastic phases of the mechanical behavior of the constitutive material. The stress distribution and the evolution of the more stressed zones in the connection are analyzed, with some focus on the complex failure mode due to bearing. The experimental setup of the tested connections and the background of the grid

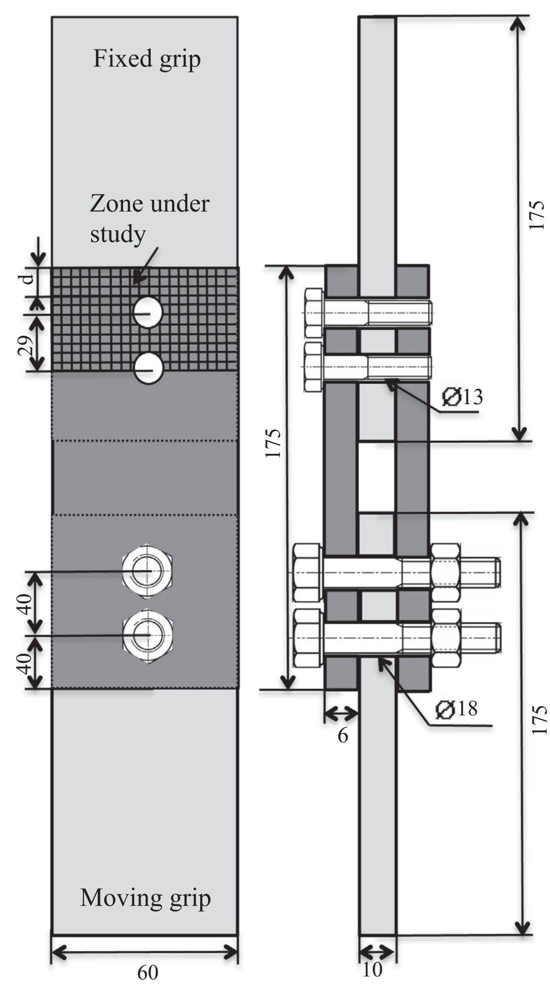


**Fig. 1.** Bolted connection specimen.