RELIABILITY ANALYSIS OF STAINLESS STEEL COVER PLATE JOINTS

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1. INTRODUCTION

Stainless steel practice in structural applications is in increasing development because of the many qualities of this material. Indeed, it has a highly ductile non-linear behavior and a substantial strain hardening capacity, which allows large energy dissipation under cyclic or accidental loading and significant force redistributions inside structures before failure. In addition, it is an esthetically attractive material, resistant to corrosion and high temperatures. Thus, it is perfectly suited for applications in steel construction and especially for structural joints where resistance and deformation capacity are required.

In the existing European design codes dedicated to steel structures, some of these qualities are taken into account but other provisions derived from those applicable to carbon steel components remain incomplete. In this paper, a reliability analysis of the behavior of a cover-plate joint, made using a numerical model, is presented. The results are used to assess and enrich the existing provisions while following the reliability objectives of the Eurocodes.

1.1. Stainless steel in structural joints

The behavior of stainless steels, contrary to that of carbon steel, is non-linear all along their deformation range and is

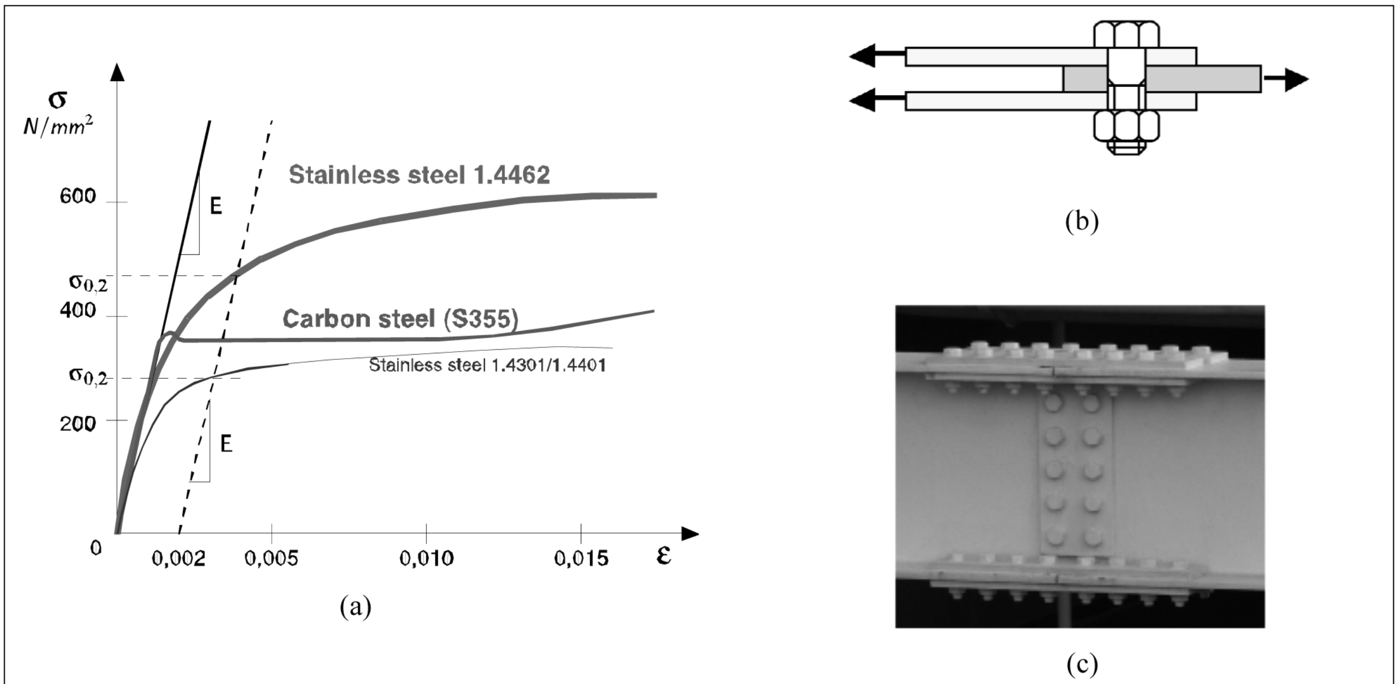

Fig. 1. Typical behavior curves (a) ; principle diagram (b) and example (c) of cover-plate joint

subject to anisotropy. In consequence, the elastic limit is conventionally defined at a plastic deformation of 0.2 % (figure 1.a). Besides, this material can exhibit an important creep in ambient temperature, which imposes to restrain long-term stresses [EUR 06].
Usual structural joints are composed of bolts working in traction, shear or a combination of both. Among the different types, cover plate joints are common because their mechanical principle is simple. Indeed, traction or compression forces are transmitted between two plates through one or several bolts in shear (figure 1.b). This kind of assembly exists also in more complex joints to realize beam continuity or beam to column assembly in which a bending moment is transmitted using cover-plate joints in the compression and traction zones (figure 1.c).

1.2. Eurocode provisions

In the European design codes, stainless steel structures are covered by the EN 1993-1-4 document [CEN 04] that compiles additions to the rules established for carbon steel to take into account the specifics of stainless steel. The main difference for structural joints is the justification of resistance in net section and in bearing. Thus, in the case of a hollowed plate in traction, the net section resistance is given by [1] :

$N_{u,\,Rd} = k_r \cdot A_{net} \cdot f_u/\gamma_{M2}$ [1]

where $k_r = (1+3.r.(d_0/u - 0,3)) \leq 1$; r is the fraction of the number of bolts in the section over the total number of bolts in the joint ; $u = 2.e_2 \leq p_2$; A_{net} is the nette section area ; d_0 is the nominal diameter of the hole ; e_2 is the distance from the center of the hole to the adjacent end, and p_2 is the transverse spacing between centers of holes (figure 2).

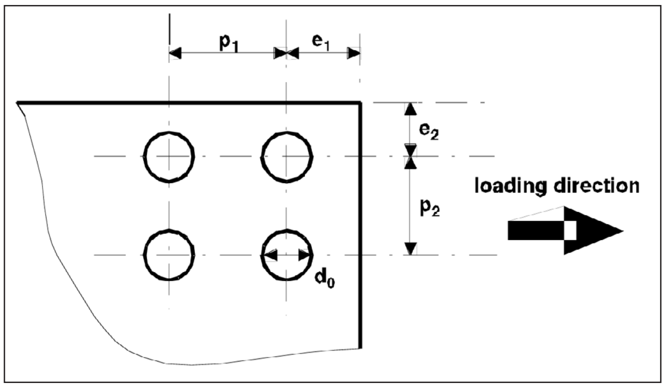

Fig. 2. Eurocode notations for the dimensions of bolted connections

The bearing resistance is given without modifications with the case of carbon steel in equ. [2] :

$F_{b,\,Rd} = K_1 \cdot \alpha_b \cdot f_u \cdot d \cdot t / \gamma_{M2}$ [2]

in which $\alpha_b = \min \{ e_1/(3.d_0) ; p_1/(3.d_0)-1/4 ; f_{ub}/f_u ; 1.0 \}$, $k_1 = \min\{ 2,8.e_2/d_0-1,7 ; 2,5 \}$ and e_1 is the distance between the center of the hole and the adjacent end of the plate, in the loading direction. Though, in the case of stainless steel, the hole deformation under serviceability loading can be critical. In consequence, a reduced value of the ultimate resistance f_u, defined in [3] is introduced in order to avoid verification under service limit state, which involves a complex determination of the deformations in the joint.

$f_{ur} = 0,5f_y + 0,6\, f_u$ [3]

1.3. Context of the study

Several studies have been conducted on stainless steel structural components [BUR 00][KOU 00][VAN 00] to assess the Eurocode 3 provisions. Among them, a particular investigation achieved at LaMI [RYA 00][BOU 02][SCI 00] was dedicated to the behavior of stainless steel cover plate joints (figure 3.a), and to the assessment of the design rules concerning the resistance, the relative joint capacity and the bearing deformation [BOU 05]. It has been demonstrated that verification under ultimate limit state loading is insufficient and can lead to unacceptable deformations in serviceability limit state. Indeed, this is hardly the case with carbon steel because of a low ratio between the ultimate and elastic limits, generally going form 1.1 to 1.5. With austenitic stainless steel, this ratio can be superior to 2 whereas the ratio between ultimate and serviceability loads is still in the range 1.35 – 1.5.
Recently, a multi-component analysis of cover-plate joints (figure 3.b) was proposed using a numerical model [BOU 08][AVE 09], taking into account material and geometric non-linearities as well as the local deformations in the contact zone between bolts and plates (figure 3.a). The results of this study were validated by comparison with experimental data on three different joints. This approach allowed to identify the influences of the sources of deformation (figure 3.a) and the main parameters involved in the global behavior of this kind of joint : the constitutive material law, the thickness of the plate, the distance of the hole to the end of the plate and its width.
Although this approach is able to reproduce accurately the global behavior of these joints, it does not consider the variability of the material characteristics and dimensions. We showed also that the analytical expressions of resistance provisioned by the design rules, which are established in the respect of a reliability target, are only partially adapted to the characteristics of stainless steel. This is why we propose a complementary study based on reliability methods using a meta-model of the limit state function built from a set of numerical results.

2. META-MODEL OF A COVER PLATE JOINT COMPONENT

In order to assess the reliability of a criterion that concerns the resistance or the rigidity of a structural joint, it is necessary to focus on the respective limit state function. However, this function involves many variables and its evaluation can be very complex so it can be convenient to make use of an alternative meta-model. This approximated model of same order can then provide quickly, through a

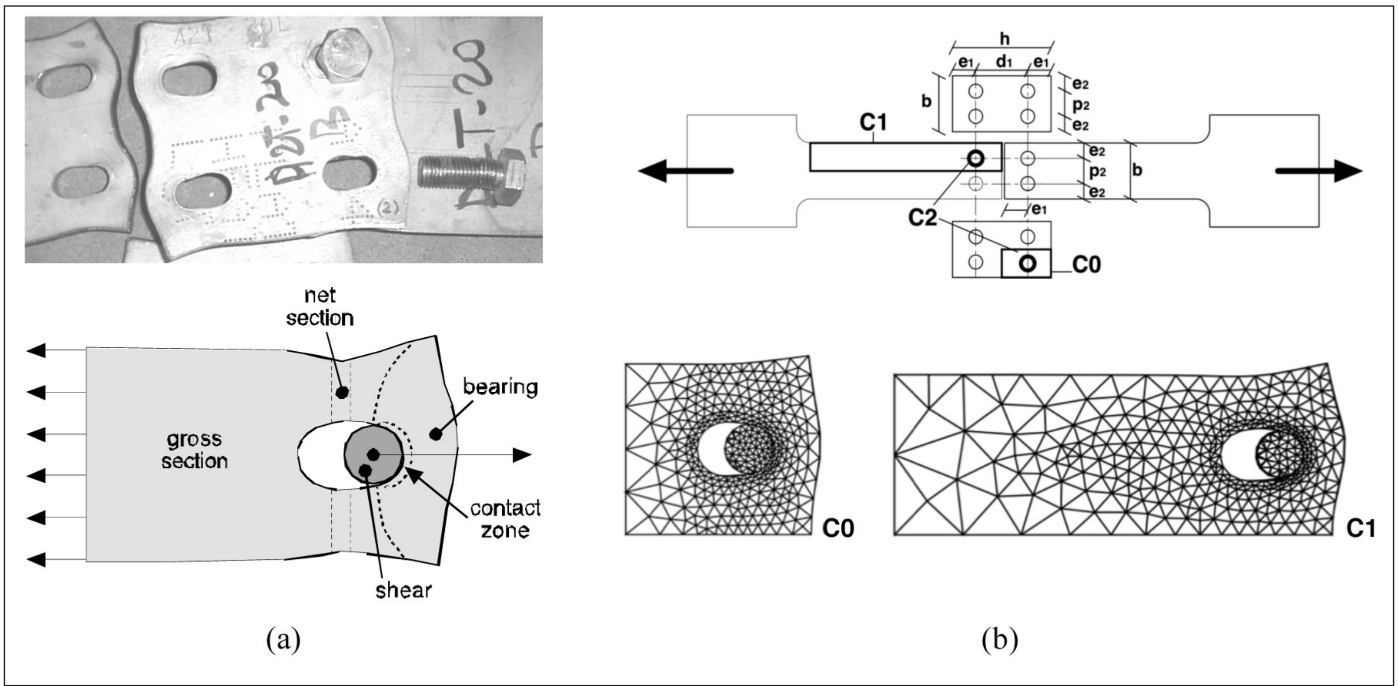

Fig. 3. Test results and deformation sources (a) ; multi-component analysis using a finite-element model (b)

unique entity, the main characteristics of the behaviors of a whole set of joints without having to achieve systematically a heavy numerical analysis. As other advantage, this model built from a fitting of several results attenuates the numerical uncertainties of each numerical non linear computation, which stabilizes the reliability calculation algorithm. Finally, it is a continuous model that allows performing extrapolations. The results from which this meta-model is built are coming from the reference model of a simple component representing an axis in contact with a hollowed plate (figure 4).

2.1. Finite element model

This model is part of an existing general joint model [AVE 09]. The axis is modeled here as a flat cylinder with a diameter d and a height twice that of the thickness t of the plate. The lower end face is restrained along z and the two ends along y and the direction x of the imposed displacement. The plate comprises a hole with a diameter d_0 situated on its longitudinal axis. Its lower and left edges are restrained transversally like the C1 component f the initial model (figure 3.b). Along z, the corners and 4 points of the lower face around the hole are fixed (figure 4).

Load is introduced as an imposed displacement on the axis of 10 mm along x, which allows going beyond the ultimate limits usually adopted [KIM 99]. The material law for the plate is derived from that of a carbon steel by a factor k. It is bilinear, with an elastic modulus E=210 GPa and such that f_u/f_y is equal to k at an arbitrary deformation level of 70 %. The constitutive material of the bolt, supplied from experimental tests [RYA 00], is a stainless steel with an ultimate limit f_{ub} = 800 MPa for an elongation of 25 %.

2.2. Experimental plan

The numerical model is used to generate the force-displacement behavior laws of a set of more than 400 joints defined by those variables (figure 4) : width b, end distance e, thickness t and the behavior law, through the k ratio. The length L of the plate and the diameters d and d_0 of the bolt and the hole are fixed. The variation range of each parameter is given in Table 1.

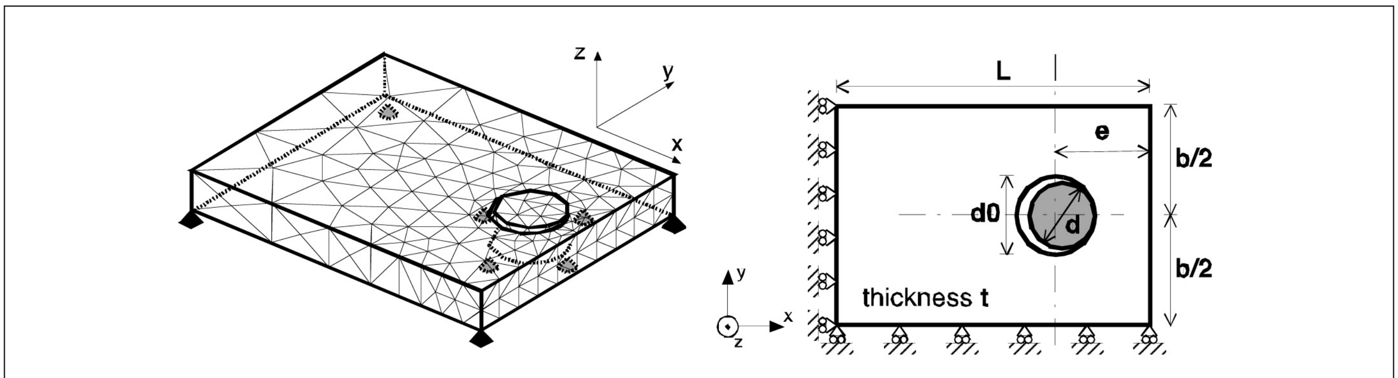

Fig. 4. Mesh, boundary conditions and parameters of the numerical model

variable parameter	value
b	30 à 80 mm
e	15 à 50 mm
t	8 à 12 mm
k	1 à 1,4
variable parameter	**value**
L	100 mm
d_0	22 mm
D	20 mm

Table 1. Parameters values for the numerical model

For each computed joint, several data are extracted from the behavior curve : the initial rigidity, the displacement and rigidity at the final state and the maximum force. In this study, secant values of the resistance for conventional displacements of 2 and 5 mm are identified, which allows qualifying the joint in terms of resistance and deformations capacity (figure 5).

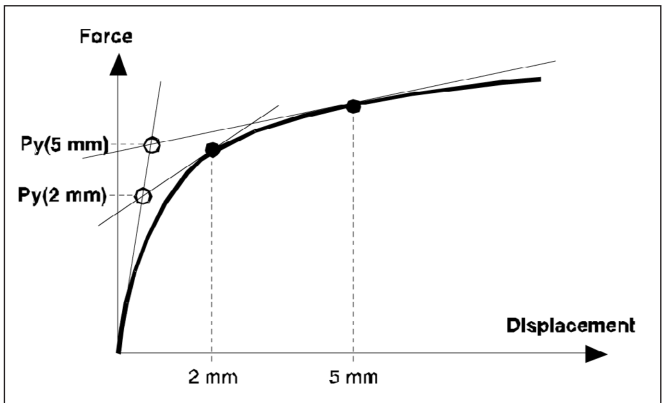

Fig. 5. Definition of the secant resistance P_y from the force-displacement response

2.3. Meta-model

The meta-model is a quadratic response surface obtained by least-square regression on the dataset provided by the results from the reference finite element model. The relative error with the raw data is less than 5 %, which ensures a good adequation in the variation range of the parameters (Table 1).

A comparison with the resistance expressions of the Eurocode 3 confirms that the kind of joint chosen for this study is mostly subject to failure in bearing, which is conform to the first experimental study [RYA 00].

Indeed, the F_{br} resistance is systematically the lowest among the studied criteria (figure 6.a). By comparison with the P_y values from the numerical model, we observe that is also a lot lower in the majority of cases (figure 6.b), which implies an underestimation of the real capacity. In this study, the partial security factor for the material is taken equal to 1 and the ultimate stress is reduced according to the ratio f_u/f_y (equ. [3]). The secant resistances identified in the model are defined as the point at the intersection between the initial tangent line and the tangent of the behavior's curve for a displacement of 2 mm and 5 mm.

3. STRUCTURAL RELIABILITY

3.1. Principle

Structural reliability consists in verifying the probability of verifying the limit state, taking into account the uncertainties due to the material and dimensional parameters, the applied loadings, the numerical models, and the conditions of construction and usage. Each limit state expresses the occurrence of a failure mode in function of parameters for which uncertainties and fluctuations can be modeled as random distributions. The purpose of the reliability analysis is to estimate the probability of occurrence of a particular failure mode. For each one, the limit state function $G(X_i,d_k)$ is defined from random variables X_i, the realizations of which are noted x_i, and from design variables d_k. By convention, this function defines the safety state using positive values. Then, the failure probability associated to the limit state is calculated by [LEM 05] :

$$P_f = \Pr\left[G\left(x_i,d_k\right)\leq 0\right] = \int_{G(x_i,d_k)\leq 0} f_{X_i}(x_i)\, dx_1 \cdots dx_n \quad [4]$$

in which f_{xi} (x_i) represents the probability density of variables X_i. However, the evaluation of the integral in [4] is complex, which led to the development of the FORM (First Order Reliability Method) method [DIT 96] that introduces a reliability indice β. This indice represents the minimal margin between the point representing the design functioning state and the point of most probable failure P* in the

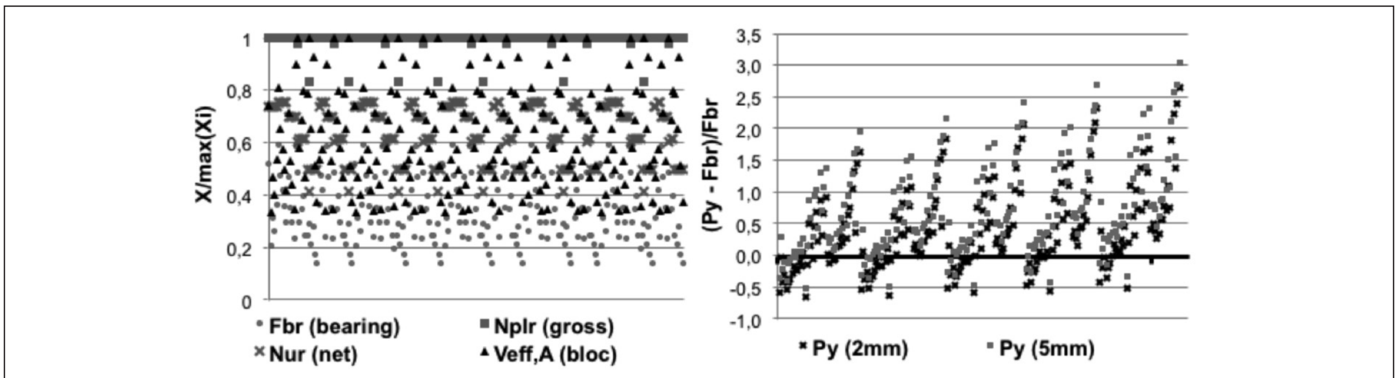

Fig. 6. Relative levels of resistance determined from different criteria of Eurocode 3 (a) ; Relative difference between the resistance at 2 mm and 5 mm from the model and the bearing resistance of EC3 (b) ; Results obtained for all specimen defined in Table 1.

space of normalized variables. This indice can be evaluated by solving the constraint optimization problem :

$$\beta = \min \sqrt{\sum_j u_j^2} \quad \text{under the condition} : G\left(x_i, d_k\right) \le 0 \qquad [5]$$

where u_j are the reduced normalized variables obtained by the probabilistic transformation T of the physical variables x_i.

$u_j = T_j(x_i, d_k)$ and $x_i = T_i^{-1}(u_j, d_k)$ [6]

Using the approximation of the FORM method, the failure probability is then evaluated using [DIT 96]:

$P_f = \phi(-\beta)$ [7]

where ϕ is the standard Gaussian distribution. The only difficulty when applying this method can then be found in the evaluation of the limit state function, which can be very complex.

3.2. Reliability of a cover-plate joint

The meta-model established in this study is used to avoid a direct calculation of the limit state function from a non-linear model, which could be costly in computing time. [CHA 02]. This reduced surface response model provides the limit load $P_y(b, e_1, t, k)$ in function of the parameters of the joint submitted to the design load P_A. As a result, the limit state function is defined as :

$G(x_i, d_k) = P_U(b, e_1, t, k) - P_A(P_G, P_Q)$ [8]

where P_G and P_Q are respectively the actions due to permanent and exploitation loads. For a given joint, the loading P_A is obtained from the existing Eurocode rules. Given that we search the variability of the resistance, the loading is defined in a determinist form by $P_A = 1.35P_{G,k} + 1.5P_{Q,k}$, where the partial safety factors ensure a low probability of occurrence for this loading during the lifetime of the structure. In consequence, the obtained probability is not that of a structural failure but that of a failure related to the design rule loading.

When evaluating the capacity corresponding to the value at the intersection of the initial stiffness and the tangent at 5 mm ($P_{y,5mm}$), the quadratic surface response is :

$$\begin{aligned} P_U\left(b, e_1, t, k\right) = & -217{,}77 + 36{,}01\ b - 22{,}26\ e_1 + 178{,}77\ t \\ & - 16{,}36\ k - 6{,}30\ b^2 - 6{,}36\ e_1^2 - 140{,}05\ t^2 \\ & - 21{,}06\ k^2 + 8{,}54\ b\, e_1 + 17{,}14\ b\, t \\ & + 11{,}21\ b\, k + 20{,}28\ e_1\, t + 15{,}08\ e_1\, k \\ & + 97{,}21\ t\, k \end{aligned} \qquad [9]$$

The considered random variables are given in Table 2. The FORM analysis leads to a reliability indice $\beta = 4{,}50$ corresponding to a failure probability of $P_f = 3{,}4 \times 10^{-6}$, which is very conservative by comparison with the objectives of the Eurocodes (10^{-2} for serviceability limit state and 10^{-4} for ultimate limit state). We observe that is is then possible to reduce the dimensions of this kind of joint, or to increase the admissible loading for the given dimensions. The figure 7 illustrates the importance of the random variables and reveals that the material ratio k and the thickness t take a great part in the failure criterion. This can be seen on the partial safety factors that must be 1.25 for k and 1.16 for t. Concerning the other parameters, nominal values are acceptable directly as partial safety factors are close to 1.

variables	distribution	mean	ecart-type
b	lognormal	60 mm	1.0 mm
e_1	lognormal	30 mm	1.0 mm
t	lognormal	10 mm	0.5 mm
k	lognormal	1.00	0.07

Table 2. Random variables for the reliability analysis

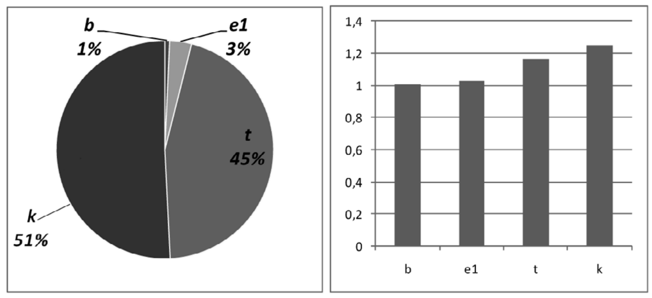

Fig. 7. Relative importance of random variables and partial safety factors

4. CONCLUSION

The presented study associates experimental, numerical and reliability analyses for the qualification of stainless steel bolted structural joints. Whereas the existing design rules applicable to carbon steel are derived for the design of stainless steel structures, the reliability analysis shows the available potential due to the great ductility and resistance of this material. The deformation capacity kept in reserve, revealed by the high reliability level and a low failure probability, demonstrates that it is possible to better exploit the qualities of stainless steel while respecting the reliability objectives of the Eurocodes. An improvement of these rules could then make of this material a more interesting alternative in structural applications. Studies are ongoing to extend this work to a broader range of geometric and material configurations of stainless steel cover plate joints.

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