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Determination of Valanis model parameters in a bolted lap joint: Experimental and numerical analyses of frictional dissipation

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ABSTRACT

In this work, Valanis model parameters, and their variation with bolt preload, were determined for a bolted lap joint, which consisted in two steel plates held together by a metric 12 screw. For this purpose, a series of transitory non-linear analyses were performed on the basis of a three dimensional finite element model of the bolted lap joint subjected to varying bolt preloads and tangential displacements. Curve fitting of hysteresis cycles obtained from numerical simulations allowed determination of Valanis model parameters as well as assessment of bolt preload influence on these parameters. In addition, the present numerical simulations provided information about the evolution of the contact state from stick to slip regimes between the bolted plates, reflecting the non-linear behaviour of the joint. Quasi-static tests at several preloads and tangential displacements conditions were conducted to validate Valanis model parameters previously obtained from numerical simulations. The present findings provided detailed information about the evolution of the aforementioned Valanis parameters with bolt preload. Thus, we confirmed that equivalent stiffness values corresponding to the macro-slip regime as well as the upper limit of the sticking regime (E_t and σ_0, respectively) are highly influenced by bolt preload levels. These results may prove useful to appropriately design bolted joints to be used under specific stiffness and damping criteria, and therefore reducing the vibration response of the joint.

1. Introduction

Bolted lap joints represent an important component of many structural assemblies used in diverse fields, such as aerospace and automotive industries, or in civil engineering applications [1–3]. These joints are typically preloaded to a constant force value normally applied to the contact surface. The preload is provided by one or more bolts, and, during service, the joint is subjected to fluctuating forces or displacements tangential to the contact surface. The complex phenomenon produced between the contact surfaces of the joint depends on a high number of parameters, being friction coefficient, slip area, and contact pressure the most important [20].

Modelling of friction phenomena in lap joints may be dealt from two different points of view. On one hand, constitutive models may be used, explaining friction on a microscopic basis and relating applied stresses to strains produced. On the other hand, phenomenological models may describe the overall relationship between the friction force and the relative displacement between the contact surfaces. From a phenomenological point of view, bolted lap joints are described by force–displacement curves, which relate tangential forces on the contact surface to the tangential displacement produced between them [4,5]. If a cyclic tangential displacement to certain amplitude is imposed, the registered curve exhibits a distinct hysteresis cycle (Fig. 1), where three regimes are clearly differentiated. Thus, when a joint is forced to a tangential displacement, d_T, this firstly behaves in a linear-elastic fashion (Line A–B) since the tangential force on the contact surface, F_T, is below the threshold of relative displacement. This initial behaviour is generally known as sticking. As the tangential displacement increases, a transition region can be observed, the micro-slip region (Line B–C), wherein the area of the contact surface that is slipping is gradually larger. Finally, increasing amplitudes of the tangential displacement provoke bolted lap joints enter into the macro-slip region (Line C–D), wherein the whole contact surface slips. Beyond that point, decreasing tangential displacements result in a sudden switch to a sticking state, reproducing the inverse of the aforementioned phenomenon (Line D–B′–C′–D′) [20].

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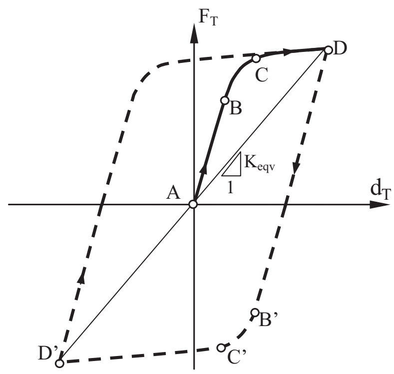

Fig. 1. Typical hysteresis cycle found for a bolted lap joint.

Several studies make use of the hysteresis cycle to determine the stiffness and damping behaviour of individual bolted lap joints to develop dynamic models of the joint within more complex assemblies. Bolted lap joints, when subjected to oscillating tangential forces or displacements, dissipate some energy, E_d, which is equivalent to the area enclosed by the hysteresis cycle (dashed line in Fig. 1). This dissipated energy determines the global damping ability of assembled structures and limits the potential harmful effects of resonant vibrations. In addition, the equivalent stiffness, K_{eqv}, of the bolted joint is determined as the ratio between the force and the maximum tangential displacement produced during the hysteresis cycle and coincides with the slope of line D–D′ shown in Fig. 1.

Phenomenological models can be classified in three groups. In the first group, friction force is assumed to be a static function of the relative slip velocity between contact surfaces, being the Coulomb model the most representative. The second group embraces dynamic models, which are based on the evolution of internal state variables. The LuGre model belongs to this second category and was first published in 1995 [6]. Finally, the third group embraces hysteresis friction models, which stem from the elasticity theory to mainly describe energy dissipation and deformation in joints. The Valanis model [7–10] lies in this latter category and it was known and extensively used in the plasticity field. Gaul and Lenz employed the Valanis model to determine the non-linear behaviour of load transfer for a bolted joint, in both micro- and macro-slip regimes, and then to simulate the response under cyclic and transitory loads [7,11]. Thus, they succeed in reproducing the experimental results of frictional behaviour of bolted joints. Eq. (1) summarizes the Valanis model [7,10]:

$$\dot{F}_T = \frac{E_0 \dot{d}_T \left[1 + \mathrm{sgn}\left(\dot{d}_T\right) \frac{\lambda}{E_0}(E_t d_T - F_T)\right]}{1 + \kappa \mathrm{sgn}\left(\dot{d}_T\right) \frac{\lambda}{E_0}(E_t d_T - F_T)} \tag{1}$$

where E_0 represents the stiffness in the sticking regime, E_t describes the slope of the macro-slip regime, the K parameter controls the influence of micro-slip, so that high values imply little influence of this regime in joint behaviour, σ_0 establishes the upper limit of the sticking regime, and the λ parameter is defined by the following relationship between the former parameters:

$$\lambda = \frac{E_0}{\sigma_0 \left(1 - \kappa \frac{E_t}{E_0}\right)} \tag{2}$$

A typical hysteresis cycle based on the Valanis model for a bolted lap joint is shown in Fig. 2. In this work, Valanis model parameters were determined for a lap joint between two steel plates bolted by a metric 12 screw. Analyses of the effects of different preload levels and maximum tangential displacements on the dissipated energy and equivalent stiffness were also conducted. These parameters were determined by fitting hysteresis cycles obtained by means of finite element modelling of the joints. Finite element models also allowed assessment of changes in the contact state of the joint as a function of tangential displacements and bolt preloads. The finite element model results were correlated and validated by experiments on a bolted lap joint subjected to varying tangential displacement amplitudes and bolt preloads.

2. Joint sample

The bolted joint studied in this work corresponds to a bolted lap joint between two steel plates. The joint consists of two steel plates, as well a M12 bolt, a not self-locking nut, and two washers (Fig. 3). The plates were obtained by means of drilling and milling processes, so that roughness ranged from $R_{a,min}=1.69$ μm to $R_{a,max}=2.49$ μm (average roughness $R_a=1.85$ μm) as measured by a portable profilometer (Mitutoyo SJ-201) on contact surfaces. To analyse the behaviour of this joint, varying preload levels, which produced normal pressure onto the contact surface of the two plates, and cyclic tangential displacements were applied. Machining of the two plates was carried out so that the joint surface lied within the medium plane of the plates, thus minimizing bending stresses. Plates dimensions are shown in Fig. 4, and their geometry was designed so that bending stresses could be avoided. Specifically, the application of the axial force lies into the contact plane, as it is shown in Fig. 6, thus minimizing bending. The rest of the

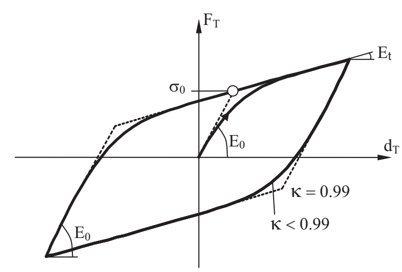

Fig. 2. Valanis model hysteresis cycle for a bolted lap joint.

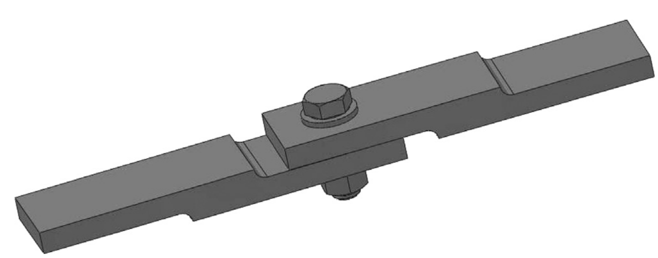

Fig. 3. Bolted lap joint.

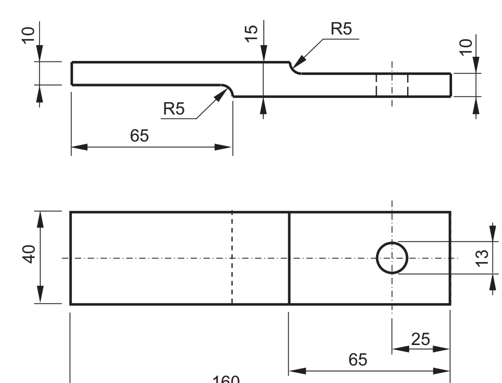

Fig. 4. Plate geometry and dimensions (mm).