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Design of experiments and energy dissipation analysis for a contact mechanics 3D model of frictional bolted lap joints

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ABSTRACT

Bolted lap joints allow structural assemblies to be made. The answer to requirements, both static and dynamic, depends on the joint behaviour. Bolted joints are a primary source of energy dissipation in dynamic built-up and space structures among others. This paper presents an analysis of a bolted lap joint, subjected to a relative displacement after applying a pre-stress on the bolt in order to characterise the joint behaviour. For this purpose a 3D modelling is made by means of finite elements, using design techniques of experiments (DOE) to fit constitutive contact parameters. The theoretical results relative to elasto-plastic hysteresis cycles of the joint are experimentally validated. Finally, the preload effect and the magnitude of the displacement on the non-linear joint behaviour are analysed to determine equivalent stiffness and dissipated energy in the hysterical loops of the joint.

1. Introduction

Bolted lap joints are often used in structures and machines to join several elements to one another and to form a structural assembly. Bolted joints are one of the main factors to determine the structural answer to dynamic requirements. Their dynamic response is characterized by the parameters of equivalent stiffness and dissipated energy depending on both the initial preload applied to the bolt and the amplitude of force it is subjected to. Bolted joints are a main source of energy dissipation in dynamic built-up, Law et al. [1], and space structures, De Benedetti et al. [2].

In order to characterise a bolted joint, several researchers make use of techniques based on the parameter adjustments which define it. In these studies the results obtained through dynamic tests are correlated to a previous joint model (see for example Miller and Quinn [3]) that depends on some parameters. Tachung et al. [4] develop a method to identify the joint parameters, rotational and translational equivalent stiffnesses and the cross coupled term between them, based on Substructure Synthesis Method and Frequency Response Functions. Song et al. [5] use Multi-Layer Feed-Forward neural network in order to determine Iwan's model parameters, which characterise the joint behaviour. Ouyang et al. [6] present a theoretical–experimental study on a bolted joint subjected to a dynamic torque load, making use of its dynamic response to adjust Jenkins' model parameters. Ahmadian and Jalali [7] make use of Incremental Harmonic Balance method to characterise the joint. Cunha et al. [8] use the technique of model adjustment in order to obtain the joint stiffness by means of experimental results of static and dynamic behaviour.

Other researchers make use of finite element models (FEM) in order to determine the parameters which characterise the joint, reproducing real load conditions. Classical references are shown in Mackerle [9] to the use of this technique for the analysis of several joint systems, including bolt joints. Oldfield et al. [10] use a 3D FEM of three components, two blocks and a bolt-nut, under harmonic loading, in order to determine Jenkins and Bouc–Wen's model parameters which characterise the simplified behaviour of a bolted joint subjected to a torsion moment. Reid and Hiser [11] make use of a 3D model with LS-DYNA in order to verify the behaviour of a joint in sliding. Crocombe et al. [12] estimate the energy dissipated by the double bolt joints of an aero-space satellite model by using a previous FE simulation of the joints compressing two aluminium plates and making use of symmetry. Kim et al. [13] compare four kinds of finite element models for bolted joints, made with ANSYS, and their subsequent use for predicting the

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stress distribution in a one-twelfth symmetric model of a low speed diesel engine. Ding and Dhanasekar [14] analyse the effect of the loss of bolt tightness into bonded-bolted steel butt joints.

This work carries out a fitting of constitutive parameter of a contact mechanics model (see Wriggers [15]) of a frictional bolted lap subjects to cycles of longitudinal shear stresses. First of all; experimental tests, in concert with numerical modelling, are employed in a parameter adjustment to determine (among others) the constitutive coefficients -static value, dynamic friction coefficient and exponential decay- of a friction Coulomb's law with velocity-variable friction coefficient, then additional experimental data are used to validate this fitting method. Secondly; the joint behaviour is analysed for hysteresis loops with different levels of pre-stress in the bolt and diverse amplitudes of longitudinal displacement, with particular attention to determine the influence of these parameters over the equivalents stiffness and dissipated energy during the reproduced hysteretic loops.

This report is organized as follows. In Section 2, we set up the parameters and equations involved in the contact mechanics model of the lap joint. Section 3 describes the equipment and the instrumentation used for testing the bolted lap joint. In Section 4, the contact parameters are fitting by using DOE techniques these adjusted values are validated in Section 5. In Section 6, we analyse the influence of bolt pre-stress and amplitudes of longitudinal displacement into equivalent stiffness and dissipated energy of the hysteresis loops. Short conclusions end the paper.

2. Bolted lap joint model under dissipative hysteresis loops

As shown in Fig. 1, the bolted lap joint analysed in this paper consists of the following components: two steel plates, two washers, a nut and a bolt (M12). Two photographs of the considered joint can be seen in Fig. 5.

In a first step the bolt is tightened to a desired value (preload or pre-stress), then it is subjected to shear forces that are transmitted by friction through contact surfaces between all of their components. The shear forces are generated by fixing the left tip of the joint while its right end is displaced along the direction of the longitudinal axe of the joint.

When the right end of the joint is subjected to a quasi-static and periodic boundary condition, see Fig. 6, hysteretic behaviour appears. The associated hysteresis loops, see Fig. 7, are characterized by the amount of energy dissipated and an equivalent stiffness.

2.1. Geometry and material properties

The dimensions of plates are shown in Fig. 2 and the rest of the components have standardized dimensions. In order to reduce bending stresses, the contact surfaces between the plates and the centroids of the edges of the joint are in the same plane.

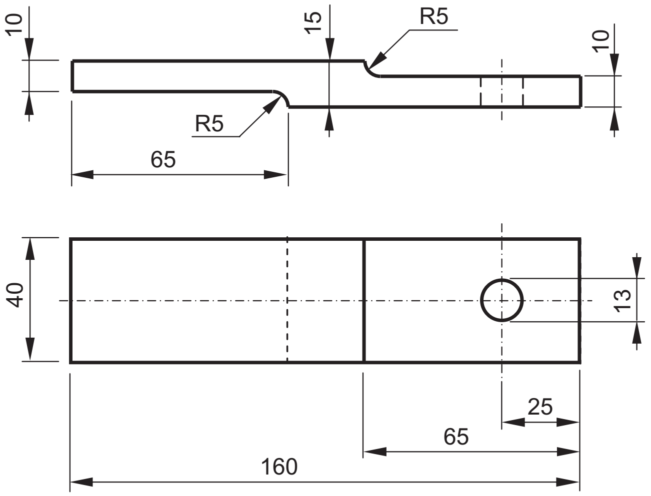

Fig. 2. Plate geometry and dimensions (mm).

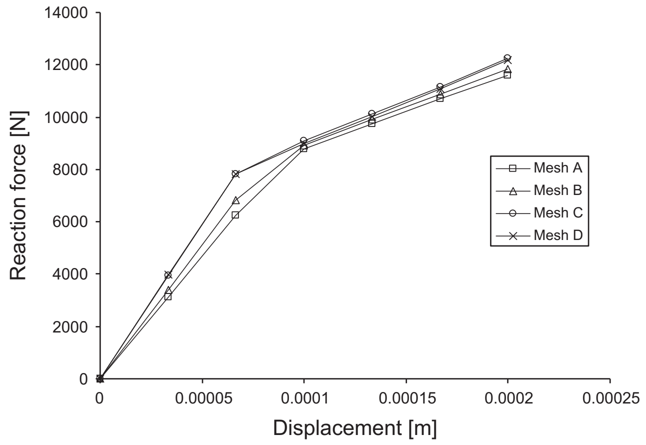

Fig. 3. Reaction force vs. displacement curve obtained from FEM simulation for four mesh sizes.

The material behaviour for all of the components is defined according to a nonlinear stress–strain constitutive law, specifically a bilinear elastic–plastic model without rate-sensitivity and with the constitutive material parameters shown in Table 1.

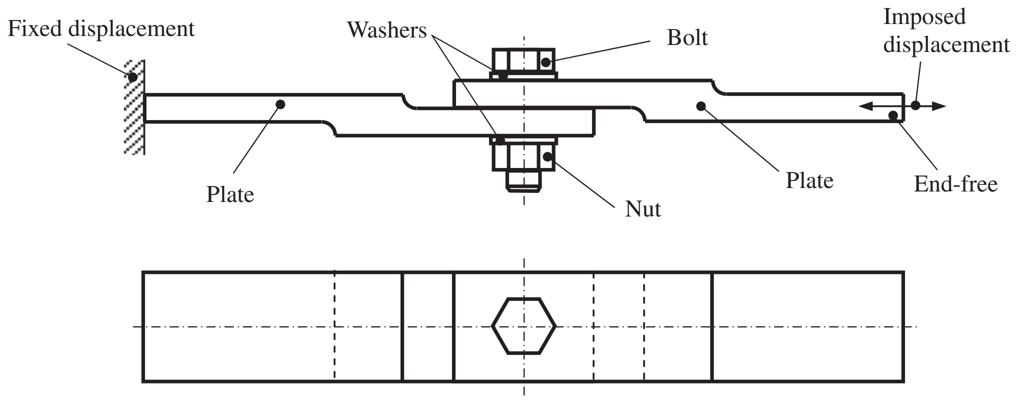

Fig. 1. Bolted lap joint.