



# Effect of contact on the elastic behaviour of tensile bolted connections



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## ABSTRACT

Both experimental evidence and 3D finite element analyses indicate that contact forces between the connected parts influence the behaviour of bolted T-stub and L-stub connections in tension. In the present paper, a mechanical model that predict the elastic behaviour of such connections is developed. The model relies on the enhanced beam theory, proposed by Baluch et al. [13], to describe the mechanical response of the flanges in both the contact and the non-contact regions. The model response shows that the contact stresses distribution strongly depends on the ratio between the length of the contact area and the flange thickness. Furthermore, the length of the contact zone in a non-preloaded connection appears to be independent from the magnitude of the external force. Several simplifications have been proposed to facilitate the determination of the separation length which is the primary unknown of the problem. To validate the analytical and calculation models, a 3D finite element model has been developed. Analytical and numerical results are in good agreement which demonstrates the validity of the proposed mechanical model. The theoretical and numerical results confirm that prying action increases with decreasing value of the ratio between the flange stiffness and the bolt stiffness.

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## 1. Introduction

One of the most significant behavioral characteristic of nearly all types of tensile bolted connection is prying action. The prying action refers to secondary forces that develop in tensile bolts in addition to tension caused by the externally applied forces. These secondary forces which are given by the integral of the normal stress distribution over the contact zone, can significantly increase the bolt force. The distribution of the normal stresses in the contact zone not only influences the tension force in the bolt but also the joint stiffness. The effect of prying action is particularly important for bolted T-stub and L-stub type connections which are the basic components of a wide range of bolted connections for beams, columns, large span trusses, chimneys, wind turbines and pylons. L-stubs are commonly used to model the tension part of ring flange connections (see Fig. 1). The tube-wall welded to the flange is subdivided into  $n_b$  L-shaped segments, where  $n_b$  corresponds to the number of bolts. The pertinence of this approach has been validated by Seidel [1].

L-stubs provide an illustration of the prying mechanism (see Fig. 2). The externally applied force  $F_T$  by the tube produces bending effects in the flanges which in turn cause contact stresses that develop near the outer edges of the flange. The force-resultant of the contact stress distribution  $Q$  is the prying force. Summing the forces acting on the flange

shows that the force  $B$  in the bolt is equal to the sum of the external load  $F_T$  and the prying force  $Q$  (see Fig. 2).

For some time now, the prying force has been represented by a concentrated force acting at or near the flange plate edges of T-stubs ([2–5]) or L-stubs (Seidel [1], Petersen [6]). In such a model, the position of the prying force does not depend on the flange geometry. Agatonovic [7] proposed to position an elastic support at the point of application of the prying action (located between the bolt centreline and the free edge) with a stiffness depending on the bolt dimensions and the flange thickness. Another approach developed by Kato & Tanaka [8] and Lemonis & Gantes [9] is to consider a fixed support at the point of transition between the contact and the non-contact regions. At this point, the curvature is null and so is the bending moment. In the elastic range, the equilibrium position thus obtained is unique and depends on the ratio between the stiffness of the flange and the stiffness of the bolt. This hypothesis is acceptable for a relatively small contact area.

Senda et al. [10] proposed to consider a linear distribution of the contact pressure. However it is shown here that the contact pressure distribution may depend on the extent of the contact area and may not be unique in shape. Bakhiet [11] has developed a model which takes into account the size of the contact area but the prying action predicted becomes null in the case of a pointwise contact at the free edge of the flange. Chakhari [12] proposed an incremental model where the flange in contact is assumed to be a Bernoulli beam resting on an elastic Winkler foundation. The stiffness of the foundation is numerically computed and depends on the bolt dimensions and the flange thickness as in the Agatonovic model. The above-mentioned analytical models rely

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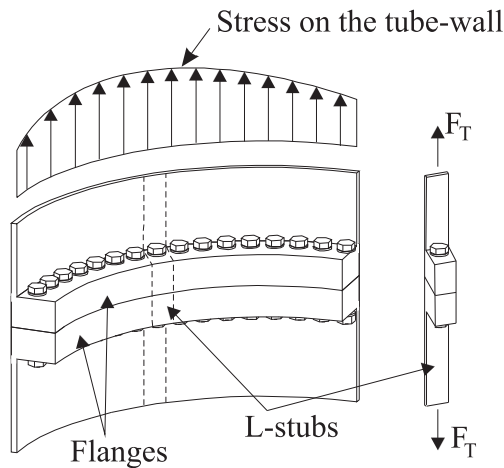


Fig. 1. Ring flange connection and L-stubs [1].

on important simplifications to circumvent the complexity of contact interaction between the flanges of tensile bolted connections. From the above discussion, it becomes apparent that the accuracy of any mechanical model for such connection is strongly affected by the prediction of the contact stress distribution between the flanges. Thus the main challenge of this problem is to provide an accurate yet simple model that reproduces correctly the contact interaction taking place between the flanges. Exploiting the “double” symmetry of the T/L-stub assembly, the flange-to-flange contact is replaced by a flange-to-rigid foundation contact interaction where the flange is modelled as a beam. Two main routes have been followed to solve this problem. In the first approach, the elastic beam is considered as a deformable elastic body in smooth contact with a rigid foundation which results in a mixed boundary-value problem ([16–18]). These mixed boundary-value problems have been solved by means of an appropriate displacement solution to the equations of plane strain linear elasticity [18]. Due to the

complexity of the solution procedure, a direct application of the above solutions to the present engineering problem seems to be cumbersome and difficult to apply in a day-to-day design. The second approach employs engineering beam theories (Bernoulli or Timoshenko) instead of continuum mechanics. The main shortcoming originates from the constraints placed on the deformation map. Indeed, engineering beam theory assumes that cross sections that are plane before deformation remain plane after deformation (plane-sections hypothesis). An equally important assumption is that those plane sections do not distort in their own planes, either. This hypothesis makes the contact stresses distribution indeterminate and therefore not unique. Furthermore, if Bernoulli kinematics is considered then the bending moment equal to zero in the contact zone as a result of the nullity of the curvature. To ease the determination of the contact stress distribution, the rigid cross-section assumption must be relaxed to permit transverse deformation while preserving the simplicity of an engineering beam theory. One possible way is to replace the rigid foundation by a semi-infinite elastic substrate or an elastic foundation and transfer the beam cross-section deformability to the foundation. A second approach consists in developing an analytical model, based on the refined beam theory of Baluch et al. [13] to investigate the behaviour of prismatic solid in contact with a smooth rigid foundation (see Couchaux et al. [15]). The effects of both the transverse and the shear deformations are taken into account.

The main purpose of this paper is to present a general analytical model for non-preloaded bolted connections in which the contact interaction between the flanges are accurately computed and so is the prying force. The main ingredient of the proposed connection model is the enhanced beam theory which allows to accurately reproduce the contact interactions between the flanges [15] as well as the shear deformability of the flange. This mechanical model is applied to analyse the behaviour of T-stubs and L-stubs subjected to a tensile force. The position of the prying force, the bolt force and the evolution of the contact pressure are particularly studied. Simplifications are proposed to ease the determination of the separation length. Predictions of this model are compared favourably against numerical simulations based on the code ANSYS V.11.

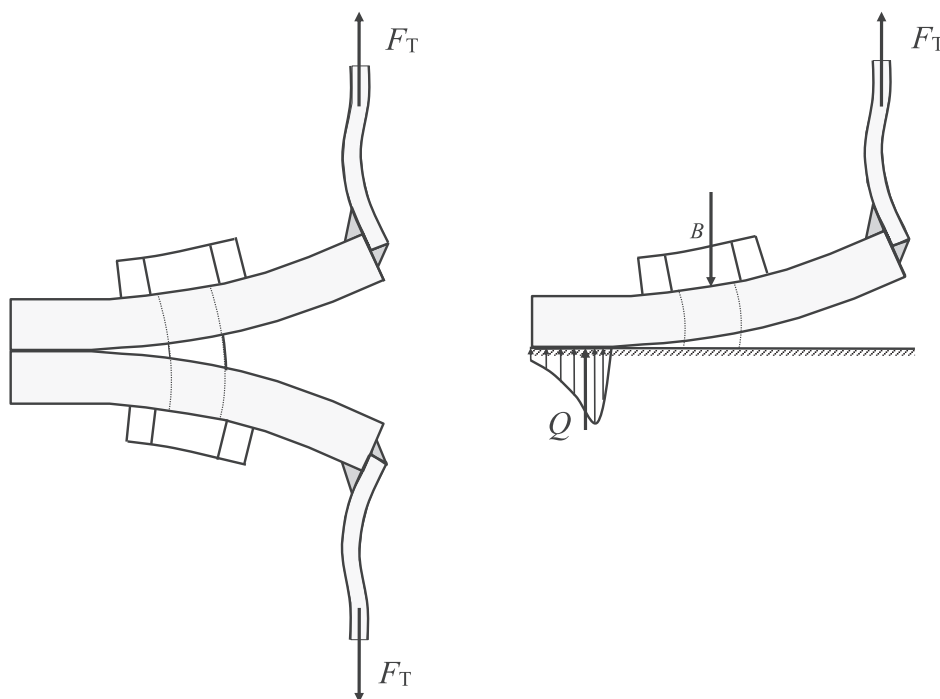


Fig. 2. L-stub in tension.

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