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Nonlinear behavior of single bolted flange joints: A novel analytical model

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ABSTRACT

Flange joints are widely used in mechanical and civil structures. In this study joint deformations are investigated and a detailed model, which can demonstrate the actual joint behavior, is developed. This is done by modeling joint laps and bolts respectively as cantilever beams and springs. Then, an accurate relation between their load and deflection is obtained. It is shown that unlike the lap joints, the flange joints should be modeled using bilinear stiffness. Furthermore, the Euler-Bernoulli theory is used to model dynamic behavior of the beams, which are connected to the flange joint. An analytical procedure is introduced to calculate natural frequencies and mode shapes of two beams, which are connected by a single bolt flange joint. Two experimental setups consisting of a single bolt flange joint specimen and beam-flange system have been designed to investigate static and dynamic behavior of the system. One of the specimens is put into different loading configurations to obtain moment-slope curve. Another setup, consisting of freely suspended beams connected by a single bolt flange joint, is used to investigate natural frequencies of the system. Comparing the theoretical flange stiffness with the experimental and FEM results shows accuracy of the proposed model. Furthermore, dynamic behavior of the proposed beam-spring model is validated using empirical natural frequencies.

1. Introduction

Mechanical joints like flanges, x-joints, lap joints, etc. are widely used in industrial, aerospace and marine structures [1–4]. Flanges mainly come in circular configuration to connect two bodies by a several number of bolts. They also come in non-circular configuration in order to connect two plates [5,6]. Some of the common applications is in connections of airplane parts, petroleum refinery towers, rocket stages and jet engine casings [7–11].

For simplicity, in order to analyze the dynamic behavior of mechanical systems, joints are generally modeled by equivalent spring and damper. In doing so, stiffness and damping of the equivalent system are empirically obtained [12–14] or numerically calculated [6,15–19]. Identifying these parameters is a fundamental step towards achieving an accurate model of mechanical systems with Flange joints. Although the flange joints have various application, their effects on behavior of the mechanical structures are not well defined and in many applications it is assumed the flange joints are rigid connections [20]. However, the previous researches reveal that this is an over estimated assumption and does not provide a good estimate of the joint characteristics [21].

One of the first studies on flange joints was done by Agatonovic in 1985 [22]. He proposed a finite element model of a pressurized bolted flange. This model consists of a single bolt and its pressurized cone, which considered as beam that lay on the beneath.

Shi et al. introduced a model for analyzing moment-deflection behavior of an endplate connection [23]. They proposed a 6-bolted joint into separate T-shaped single bolt joints and obtained a beam-based model for each of them. The complete model constitutes of separate T-shaped models which were assembled together. Luan et al. presented a simplified nonlinear model for the analysis of pipe structures with bolted flange joints [24]. They segmented the full circular flange into separate single bolt models and extract a bilinear longitudinal spring model for each of them. Schwingshackl et al. investigated the nonlinear dynamic behavior of bolted flange joints in jet engines [6]. They demonstrated that the maximum energy dissipation occurs on bolt flange contact. Wu et al. obtained nonlinear dynamic behavior of bolted flanges under various loadings [18]. They found that despite elastic deformations the system has non-linear behavior due to changes in the contact area between the two edges. Meisami et al. studied static behavior of the flange joint under axial and lateral loadings [25]. They show that the joint has nonlinear behavior under axial and lateral loadings. Several studies are reported also investigating stress and strength of bolted flange joints [26–28] which are not covered by this literature review.

Due to complexity of modeling and analysis of the bolted joints with several bolts in different configurations, the joints generally divided

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Nomenclature

A	Cross section area (m^3)
E	Young's modulus (N/m^2)
I	Area module of inertia (m^4)
K	Stiffness (N/m, Nm/rad)
L	Beam length (m)
l	Distance to O (m)
R	Average diameter of the bolt's head (m)
t	Thickness (m)
δ, γ	Deflection (m)
θ, φ	Slope (Rad)
ν	Poisson ratio
ω	Natural frequency (rad/s)

Superscript

$+$	Positive deformation and slope
$-$	Negative deformation and slope

Subscript

B	Bolt
fl	Flange
l	Longitudinal
t	Torsional

into separate single bolt sub-sections. In previous studies, which are investigated the multi-bolted joints (lap joints, flanges and endplates) generally the equivalent single-bolted models are considered [11,24,29]. But in case of the single bolt joints most of the investigations are focused on the lap joints. Ahmadian and Jalali [30–32], Iranzad and Ahmadian [33] and Abad et al. [13] investigated the dynamic response of two beams connected by a single bolt lap joint in order to identify dynamic behavior of the joints. The main purpose of these experimental studies is to estimate the damping behavior of the joint.

In this study, a novel theoretical model for the flange joints, which simulates the actual joint behavior, is proposed. Unlike the previous investigations [25], not only the static behavior of the joint is considered but also the dynamic behavior is studied analytically and experimentally. It should be noted that, in this study, the aim is to obtain the dynamic behavior of the beam-joint system, so only deformation properties of the joint are considered and the strength is not concerned. This model helps researchers in this area to obtain more accurate equivalent joint stiffness. Furthermore, a new analytical procedure is introduced to calculate natural frequencies of the mechanical elements which are connected by a single bolt flange joint. Obtaining analytical solution of a problem is important because:

- In comparison with numerical and experimental solutions, it can be more accurate.
- It can facilitate evaluation of mechanical parameters effect on the system.

To achieve this, first, the joint was modeled as cantilever beam and the nonlinear springs were considered to analytically obtain the joint stiffness. Then, assigning appropriate conditions, natural frequencies and mode shape of a system consisting of two beams connected to a single bolt flange joint was extracted. Two test setups were configured to verify the static and dynamic responses of the system. The first one was used to test static moment-slope and verify the analytically obtained joint stiffness. The second setup is used to validate the calculated natural frequencies of the beam-flange system. The novelties of this study include:

- Introducing a new analytical formulation to calculate the stiffness of single bolted flange joints
- Introducing a new equivalent model of a system consisting of two beams connected by a single bolt flange joint
- Introducing a new analytical method to calculate natural frequencies of the system consisting of two beams connected by a single bolted flange joint

2. Material and methods

2.1. Problem statement

This paper focuses on deformations of single bolt flange joints and develops a novel detailed analytical model of the joint structure, which can demonstrate the actual joint behavior. For this purpose, the joint laps are modeled as cantilever beams and the bolt modeled with two longitudinal and torsional springs. Then, an analytical model of a system consisting of two beams connected by a single bolt flange joint is developed using Euler-Bernoulli beam theory having free-free boundary conditions and appropriate compatibility conditions at the center. Finally, natural frequencies of this system are obtained and compared with experimental frequencies.

2.2. Analytical joint modeling

2.2.1. Equivalent model of the flange joint

Unlike the flange joints, in bolt lap connections the bolt is perpendicular to the beam. Because of the bolt lap joint geometrical symmetry, the lateral deflections of the joint under positive and negative moments are the same. Fig. 1 compares the bolt lap and flange lap connections in different lateral deflections. As shown in this figure the lateral deflections of the flange joint under positive and negative moments are different. Therefore, it can be concluded that lateral dynamic behavior of the flange joint can be nonlinear.

For theoretically analyzing, the dynamic and static behavior of the flange joint, it should be simulated using equivalent damping and stiffness. Fig. 2 depicts the equivalent model of the beam-flange system consisting of two beams which are connected by a bilinear torsional and longitudinal springs. The joint behaves differently under positive and negative moments, so the torsional behavior of these joints should be

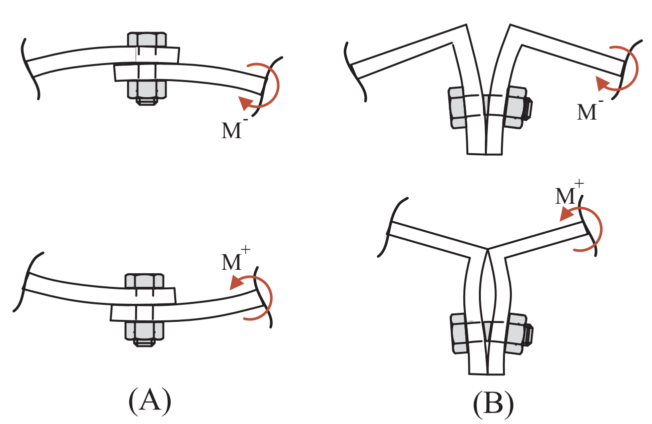

Fig. 1. Lateral behavior of bolt lap (A) and flange lap (B) joints under the positive and negative loadings.