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Effect of Preload on Natural Frequency of Bolted Joint under Impact Loading

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***Abstract*—This The bolted joint is the best choice for detachable assembly of components in structures and machines to maintain integrity in fastened structure due to their high reliability, strong load bearing capacity, easy maintenance and inspection at low cost. However, in many applications bolt connections are often subjected to low velocity impact loading during their service life which reduce the preload on bolted joint and leads to failure of engineering structures. Reduction in preload (Loosening) of bolted connections in a structure can significantly reduce its load-bearing capacity. Detecting loosening of bolted connections at an early stage can prevent failure of the structure. Due to the complex geometry of a bolted connection, it is difficult to detect loosening of a bolted connection using conventional nondestructive test methods. A vibration-based method that uses changes in natural frequencies of a structure is effective in detecting loosening of bolted connections since the method focuses on detecting a stiffness reduction of bolted structure.**

The present work is focused on analyzing effect of preload on natural frequency of bolted joined structure subjected to low velocity impact loading. The effect of preload is carried out in experimental analysis and simulated by Pre- Stressed Modal Analysis.

Keywords— Preload, Low velocity impact, Natural frequency measurement, Bolted joint.

I. INTRODUCTION

The bolted joint is the best choice for detachable assembly of components in structures / machines due to their high reliability, strong load bearing capacity, easy maintenance and inspection at low cost to maintain integrity in fastened structure. Bolted joints have a complex nonlinear behavior which may arise from the material, geometry and dynamic properties of joints. In general, the preload force determines the strength of the joint. However, in many applications bolt connections are often subjected to external cyclic dynamic loads, such as impact and vibration which decreases the preload on bolted joint leads to the failure of engineering structures. The two most widespread causes of failure of threaded fasteners subjected to cyclic dynamic loading are fatigue and self-loosening. Loosening is often found in a bolted joint subjected to transverse or shear load and low velocity impact load. Loosening is the gradual loss of preload in the bolted connection under cyclic external loading, especially transverse and low velocity impact loading which result in a decrease in structural stiffness ultimately changes in natural frequency or the separation of clamped members which results in risks of failure for any machinery or equipment [6]. The loosening characteristics greatly depend on the joint configuration, material of each part of the structure and loading condition to which a bolted joint is subjected. As the strength of the bolted joints is mainly dependent on the preload force, the preload has a significant effect on the response of the bolted joint to dynamic or shock loads. Since, bolted joints constitute an integral part of many structural components; this directly implicates the necessity to investigate the mechanical response of the bolted joints under a variety of loading rates to ensure structural integrity.

R. A. Ibrahim et al. [9] studied the problems of joint uncertainties and relaxation. Mahesh Patil et al. [6] explained contribution of applied load on the bolt load in a preload tensile joint depends on the stiffness ratio of the bolt and the joint cycle. N. Tanlak et al. [7] studied the bolted joint to develop computational efficient and accurate finite element model of bolted joint under impact loading. S. Narkhede et al. [10] described FE modeling methodology for bolted joint representation in crash FE models. Kumarswamy et al. [5] developed computational modeling procedures that provide structural analysts an improved physics-based shock model for combat vehicles. Andrew Joe Vander Klok et al. [1] shows that the kinetic friction forces are directly related to the loading rate imparted upon the joint. Sudhir Kumar Panigrahi et al. [11] simulated the various operations viz. modal, harmonic response and transient dynamic analyses to find out different results in ANSYS. I. Piscan et al. [4] studied parametric estimation model for identifying bolted assemblies for a rectangular and cylindrical structure using frequency response functions (FRFs). Pejman Razi et al. [8] developed, refined and enhanced the vibration-based health monitoring strategy for onshore and offshore pipelines with bolted joint. Charles et al. [2] experimentally proven that the linearity of the response varies abruptly with increase in preload and extremely reliant on the initial preload, but high preload levels can also leads to damage sensitive instrumentation packages. Weiwei Xu et al. [12] show that the modal frequency increased with increasing preload, but remained approximately constant for preload is larger than 30% in the bolt yield strength. Deepak Somasundaram et al. [3] analyze response of a bolted joint subjected to high and medium shock loads under goes elastic and plastic deformation at varying conditions of preload by using experimental and finite element method.

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From the literature review it is found that the modal analysis is effectively used in determining the vibrational characteristics such as natural frequency and mode shapes of a structure. The response of any structure subjected to the impact analysis depends on the natural frequency of the structure. Therefore it is crucial to check the natural frequency of the structure while doing transient or dynamic FE analysis. The main objective of this paper is to study the effects of preload on the change in natural frequency of the bolted structure using experimental and finite element analysis.

II. PARAMETRIC STUDY

As this is an impact analysis, wave propagation in the structure is important, therefore experimental impact test and Pre-Stressed Modal analysis is used to detect change in natural frequency of bolted structure.

A. Experimental Analysis

The experimental setup for studying transient behavior in a simplified bolted joint structure such as cantilever beam with bolted lap joint subjected to shock / low velocity impact by using low impact test (Bump Test). This low impact test setup consists of single lap cantilever type bolted structure made up of two fastened plates having M12 sized bolted lap joint at center, instrumented impact hammer, cables, accelerometer, FFT device and user interface as shown in Fig. 1

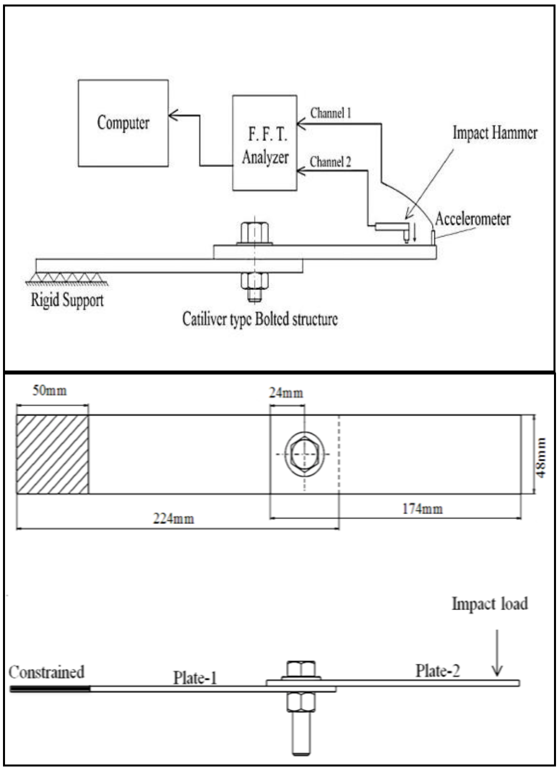


Fig.1. Experimental Setup

The Bump Test is carried out by using FFT Analyzer by tightening the bolted structure at torque 50 Nm, 60 Nm, 70 Nm, 80Nm, 90Nm, 100Nm and 110Nm so the preload on the bolt shank caused by these pre-torques is 20.829kN, 24.995kN, 29.161kN, 33.327kN, 37.493kN, 41.667kN and 45.833kN respectively to obtain frequency response of bolted structure at these torque.

B. Finite Element Analysis

1) Contact conditions

The stiffness of the system depends on the contact status. When forces are applied, there is a probability of penetration of elements of contact and target faces which can be minimized by giving proper formulation of solver and appropriate contact type between connections of assembly. There are five contact interactions are established for all contact surfaces in the finite element model are shown in Table I.

TABLE I. Contact conditions

Sr. No	Contact	Target	Type of Interaction	Formulation
1	Nut	Plate-1	Frictional	Augmented Lagrange
2	Bolt	Nut	No-separation	MPC
3	Washer	Plate-2	Frictional	Augmented Lagrange
4	Bolt	Washer	Frictional	Augmented Lagrange
5	Plate-2	Plate-1	Frictional	Augmented Lagrange

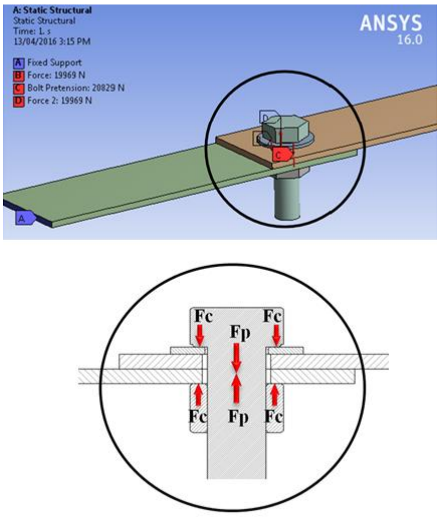
2) Meshing

All components of bolted structure are meshed by using Hex Dominant method with Quad/ tri mesh type having mesh size 2mm with fine relevance and span angle center formed total 66049 nodes and 13994 elements.

3) Loading and Boundary condition

All degrees of freedom of all nodes and elements of outer left side surface of plate-1 are fixed support. While tightening nut and bolt by tightening torque, the washer face of bolt head and nut i.e. contact face transmit clamping force (Fc) to face of washer and fastened plate i.e. target face respectively which help to clamp fastened plates together. The contact faces apply uniform distributed load on the target faces. The applied clamping forces are equal in magnitude but opposite in direction along axial direction of bolt shank. Also the preload force (Fp) is applied on the cylindrical surface of the bolt shank along the axial direction which is equal in magnitude but opposite in direction of each other as shown in Fig. 2.

To simulate experimental results, Finite Element Analysis i.e. Pre-Stressed Modal Analysis of bolted structure at constant tightening torque 50 Nm is carried out at 20.830kN preload (Fp), 19.969kN clamping force (Fc) and 1N impact load at constant initial tension (Ft) 40.798kN. The comparative results for first five modes of vibration are shown in Table II. Also same Pre-stressed Modal Analysis is carried out at different loosening torque to detect effect of loosening torque by assuming 100Nm is a full tightening torque which loosened by half, quarter and three-fourth of that i.e. tightening torque 100Nm, 50 Nm, 25 Nm and 12.5 Nm at preload (Fp) 41.659kN 20.830kN, 10.415 Nm and 5.207kN respectively.



Force-1= - Force-2= Clamping Force (*Fc*)
Bolt- Pretension = Preload (*Fp*)

Fig.2. Fixed support and forces acting on bolted joint

TABLE II. Validation of FEM results

No. of Modes	Natural Frequency (Hz) at 50Nm Tightening Torque by using		% Error
	FEM	***BUMP Test***	
Mode-1	3.580	4	-11.73
Mode-2	60.695	57	6.088
Mode-3	111.86	110	1.66
Mode-4	277.47	278	-0.19
Mode-5	337.93	333.5	1.31

III. RESULTS AND DISCUSSION

As preload or tightening torque on bolt increases, the natural frequency goes on increasing up-to certain limit of tightening preload but after that there is a reduction in natural frequency because after certain limit of tightening, washer face of bolt starts cutting washer and ultimately reduces the stiffness of bolted structure and again goes on increasing with increasing preload as shown in Fig. 3.

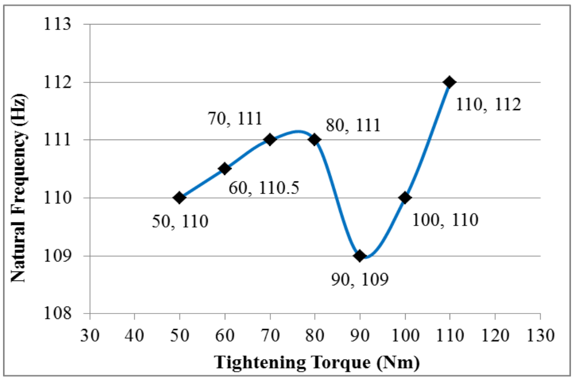


Fig.3. Graph of natural frequencies with respect to tightening torque

The first five mode shapes by pre-stress modal analysis are taken at 50Nm tightening torque concern with experimental results as shown in Fig. 4, Fig. 5, Fig. 6, Fig. 7 and Fig. 8. Out of these Mode-2 shows lateral relative movements between fastened plates were as Mode-3 shows longitudinal relative deflection between those plates i.e. loosening between fastened plates.

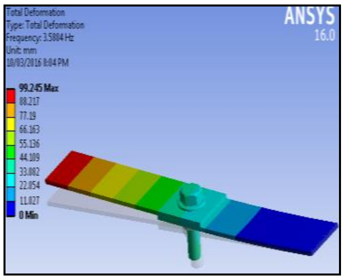


Fig. 4. Mode- 1

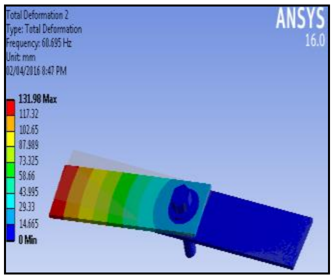


Fig. 5. Mode- 2

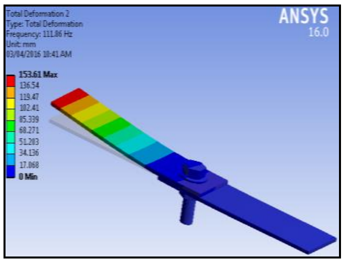


Fig. 6. Mode- 3

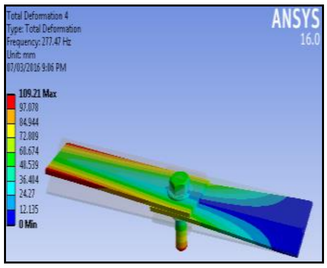


Fig. 7. Mode- 4

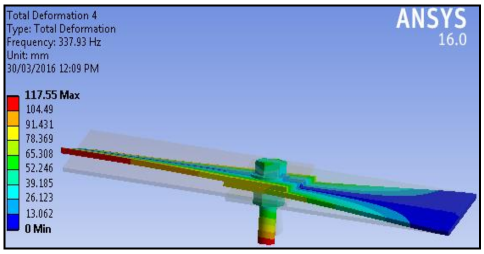


Fig. 8. Mode- 5

FEA shows that as preload or tightening torque on bolt increases, the natural frequency goes on increasing up-to certain limit of tightening torque but after that there is a reduction in natural frequency and it decreases up to preload equal to initial tension which ultimately reduces the stiffness and again increases with increasing preload on bolt and decreases linearly with decreases in preload as shown in Fig. 9 and Fig. 10.

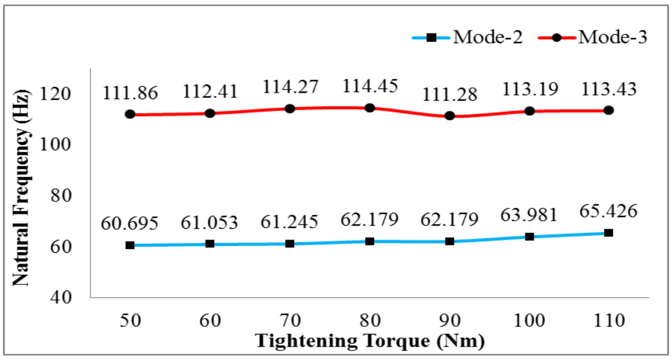


Fig.9. Graph of natural frequencies with respect to tightening torque

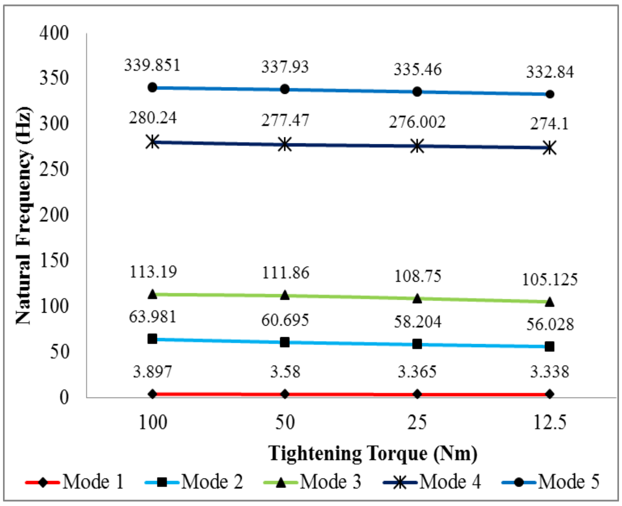


Fig.10. Graph of natural frequency with respect loosening torque

IV. CONCLUSIONS

- As preload increase the natural frequency increases up to certain preload and then decreases up to preload equal to initial tension and again increases with increasing preload on bolt.
- Reduction in natural frequency between fastened components increases with decreasing preload on bolt and nut of bolted joint linearly.

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