Pre-Stressed Modal Analysis of Composite Bolted Structure

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Abstract : Threaded fasteners are one of the most common means of joining parts of assemblies to maintain integrity of isolated elements of mechanical structures and machines used in various applications due to their high reliability, strong load bearing capacity, easy maintenance and inspection and its capability of being mantled and dismantled using simple tools at low cost. Mounting of a bolted joint usually consists of application of relative rotation between screw and nut until installation of desired preload. Bolted structures in their service life, subjected to transverse and impact loads which may result in reduction in preload on bolted joint which causes periodic retightening of threaded fasteners and high maintenance cost. The objective of this study is to identify different parameters such as excitation amplitudes, material of threaded fasteners, bolt preload, configuration of joint & structure, anti-loosening components contributing to the loosening of bolts due to low impact loading and feasibility of composite fasteners. As non-linear behaviour of bolted structure as well as numerical models has a high computational time & cost, Experimental & Finite Element approach is adopted.

***IndexTerms* - Ansys 15.0, Bolted Connections, FEA, Lap joints**

I. INTRODUCTION

For flexible and detachable assembly of components in structures and machines to maintain integrity in fastened structure, commonly used method is bolted joint. Some of the major reasons for the selection of bolted joints are high reliability, strong load bearing capacity, easy maintenance and inspection at low cost. The dynamic characteristics and reliability of built-up structures depend to a great extent on the dynamic properties of the bolted joint. Complex nonlinear behaviour shown by bolted joints arises from the material, geometry and dynamic properties of joints.

It is observed that it is the preload force which determines the strength of the joint. Greater is the preload force, joints are stronger and more fatigue resistant. But in all applications & situations, it is not possible that all bolted joints are subjected to the same load conditions. Due to this, there is a degree of uncertainty in the preload in each joint.

In many applications like in combat vehicles, chassis, suspension, machines bolt connections are often subjected to external cyclic dynamic loads, such as low velocity impact, vibration, and thermal stresses during their service life and bolt loosening leads to the failure of engineering structures. In addition, there is also relaxation in the preload due to environmental conditions once the system is placed in service

Threaded fasteners are ubiquitous in engineering assets like Industrial, aeronautical, Automobile, Marine and railway applications, performing a critical role of transferring loads among interconnecting components. Bolted structures in their service life, subjected to vibrations and impacts which may result in critical damage either from self-loosening or from catastrophic failure. So effectual inspection and monitoring is necessary to study and examine modes of vibration, anti-loosening methods, Configuration of joint, Material of fasteners and dynamic behaviour of a simple bolted assembly subjected to quickly varying low impact load.

1.1Generation of Forces in nut and bolt

Before considering forces acting on nut bolts we have to understand role of preload in loosening.When preload is insufficient to prevent the external applied forces, these forces overcome the clamping force acting between the joint faces. This causes loosening of bolted joint in structures and machines.Preload on bolt is nothing but an initial tensile force for Bolt-nut assemblies for ideal tightening Hence, preload or the torque used to tighten the bolted joints is an important factor that affects the response of the structure subjected to static or dynamic load.

To understand the forces acting on bolts, they can be compared with springs in tension as shown in Figure 1. Rotating the bolt, which in turn stretches the spring, generates the preload force. If bolt is rotated, the more it stretches and generates more preload or tension. Bolted joints can be loaded with shear force, tension force, impact force or a combination of these. In a joint loaded in tension the joint separating forces are opposed by the preload force on the

The ultimate strength of the joint is limited by the strength of the bolt. Nevertheless, the higher the preload force the better the joint, because it will prevent the assembled parts from moving and the joint from loosening. A highly preloaded joint is also more resistant to static, cycling and shock loads.

In general, the preload force determines the strength of the joint. Joints are stronger and more fatigue resistant with greater preload force. 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.

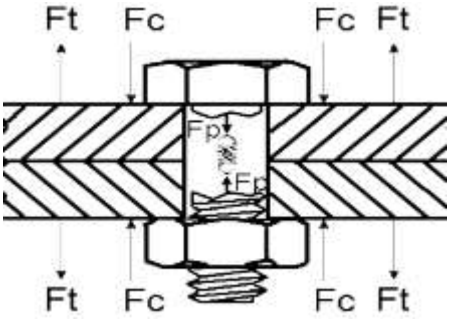


Fig. 1.Generation of different forces in bolted joints when compared with spring
Where, Fp = Bolt Pretension / Preload, Ft = Tension Force, Fc = Clamping Force

1.2Calculation of Forces in nut and bolt:

The clamping force is nothing but the force at which fastened plates hold together as expressed by following equation (Kumarswamy 2010):

Relation between The clamping force (Fc), preload force (Fp) and the tension force (Ft) developed in the bolted joint is given by,

$$Fc = Fp - Ft \qquad (1)$$

The initial tension i.e. Ft can be calculated by the following equation:

$$Ft = K \times A \times S \qquad (2)$$

Where,
Ft = Initial tension
K = Constant which ranges from 0.75 to 1.0
A = Tensile stress area
S = Proof strength.

Proof strength is the maximum tensile force that does not produce a normally measurable permanent set of deformation. Generally, this is little less than the yield strength of the material.

tightening torque or pre-torque to the initial tension is calculated by following equation:

$$T = K \times Fp \times D` \qquad (3)$$

Where,
T = Pre-torque / tightening torque
Fp = Preload or pretention force
D` = Nominal diameter of the thread
K = Constant K ≈ 0.2, for most small to medium size bolts.

II. LITERATURE REVIEW

For the proposed work, analysis and review of previous work done by researchers is taken into account. Contribution of various researchers in the analysis of loosening behavior of bolted structures is summarized. Also different research issues are presented. Research on loosening of threaded fasteners due to vibration spans nearly six decades and loosening of threaded fastener was observed in middle of nineteenth century. The focus was pre-stressed modal analysis of bolted joint to predict and reduce loosening. For this, different research papers were studied and considering the research issues, objectives are declared.

Junker (1969) identified fundamental aspects of loosening. Hence to find minimum shear force required which causes loosening and to understand mechanism of loosening,

New experimental and three-dimensional finite element analysis results are helpful. In some cases, it was verified that loosening in joints occurs due to localized slip when the fastener is subjected to dynamic shear force about half the magnitude required to cause complete slip at the fastener bearing surface.

A joint ASME/ANSI subcommittee was formed to study the problem of vibration-induced loosening in the early 1980s.As part of this committee; Kerley presented a comprehensive research plan for the study of loosening of threaded fasteners.

ZhenZang, Mengbing Liu, Zang king Su, Yi Xiao(2017) developed method for identification of bolt loosening & quantitative estimate of residual torque.[1]

P. Langer, A. Hoppe, C. Guist, S. Marburg(2017) Presented simple method for modeling bolted joint in abaqus[2]

Jianhua Liu, Huajiang Oyang, Jinfang Peng(2017) observed that with the increasing preload and the decreasing excitation amplitude, the bolted joint is not prone to loosening.[3]

Jianhua Liu, Huajiang Oyang, Jinfang Peng(2016) showed that clamp force decreases rapidly in the early stage because of the cyclic plastic deformation, and then slowly because of fretting wear in the later stage.[4]

Shriram Dravid, Karthikey & ManojChouksey(2014) studied role of Washers in Controlling loosening of bolted Joints[5].

FeblilHuda, ItsuroKajiwara & Naoki Hosoya(2013) proposed Vibration testing and health monitoring system based on an impulse response excited by laser to detect bolted joint loosening.[6]

Febli Huda, Itsuro Kajiwara, Naoki Hosoya, Shozo & Kawamura(2013),showed that various loosening states and their positions can be effectively identified by using the RT method.[7].

Ravinder Kumar(2013),analyzed that lateral vibration have prolonged effect than longitudinal vibration in loosening.[8]

Olfa Ksentini, Bertrand Combes, Mohamed Slim Abbes & Alain Daidie(2013), studied critical damage from self-loosening or Bolted joints used in aeronautical structures under vibrations.[9]

Naoya Nishimura, Katsuhiko Murase, Toshio Hattori & Takeru Watanbe(2013), showed that The critical relative slippage decreases with a decrease of the bolt axial tension[10]

Anirban Bhattacharya, Avjit Sen & Santanu Das (2012), investigated the anti-loosening characteristics of threaded fasteners under vibratory conditions and concluded that, Along with bolt material, washers plays important role in locking.[11]

Toshio Hattori, Minoru Yamashita, Hiroki Mizono & Tomohiro Naruse(2010), developed estimation model of critical relative slippage providing upper limit to prevent loosening.[12]

J.A. Sanclemente, D.P. Hess(2007), analysed that optimum

Conditions to avoid fastener loosening are high preload, low modulus of elasticity, large diameter, lubrication, tight fit and fine threads. They developed a statistical model is developed to define optimum conditions for these factors essential for proper functioning of joint.[13]

N.G. Pai, D.P. Hess(2003), observed that location of the fastener is can alter the dynamics of the structure, also they observed that shifting the external load frequency by a few Hertz away from the natural frequency of the compound beam, reduces loosening.[14]

M. Bhusnar, S. S. Sarawade(2016),carried Modal Analysis of rectangular plate with lap joints to analyze failure using natural frequencies occurring in different mode shapes[15]

Kumarswamy Karpanan Nakalswamy studied & analyzed bolted joints experimentally & numerically[16].

Some of the important points can be detected from literature review are as follows.

1. The response of bolted structure subjected to the impact analysis depends on the natural frequency of the structure.
2. The modal analysis can be effectively used in determining the vibration characteristics.
3. Optimum location of fasteners is helpful for reducing loosening.
4. Among all the numeric methods, FE analysis is commonly used for pre-stressed modal analysis, Ansys and Abacus are mostly used for FE analysis
5. Bolt preload is an important factor that affects the strength and response of the Structure.
6. Loosening causes severe damage if it is not monitored frequently.
7. Anti-loosening devices should be carefully chosen according to application of joint.

III. EXPERIMENTAL SET UP

3.1 Layout

Experimental set up consist of impact hammer, FFT analyzer & Graphical User Interface i. e. Digital computer. Simple Layout of set up can be as shown in figure given below.

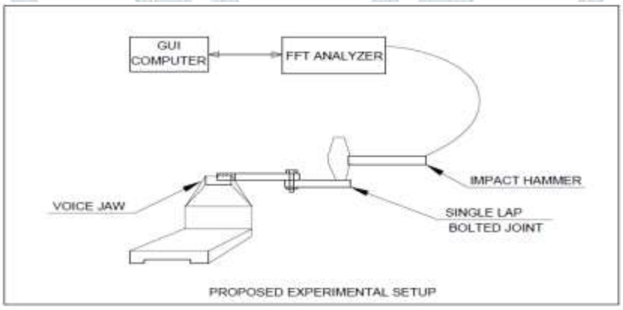


Fig. 2 Important experimental set up components

3.2 Experimental procedure

Suitable plate dimensions are chosen and material is decided depending upon experimentation for the same.

2. Bolt and nut are selected according to hole drilled in plate.
3. Plate thickness should be kept minimum i.e. 5mm to get better results of vibration
4. Single lap bolted joint specimen is prepared for experimentation. Tightening torque is applied with help of torque wrench.
5. One of the ends is kept fixed by holding it in voice and other end is kept free to make cantilever beam.
6. FFT analyzer is checked for all connections i. e. with graphical user interface and impact hammer.
7. Impact hammer is tested for repeatability at different locations of free end of plate.
8. Readings are taken with impact hammer

3.3 Specimen Dimensions

Nut bolt selected is glass fiber nut bolt with M10 X 30mm with pitch of 1.5mm.

Hole diameter= 10.5mm

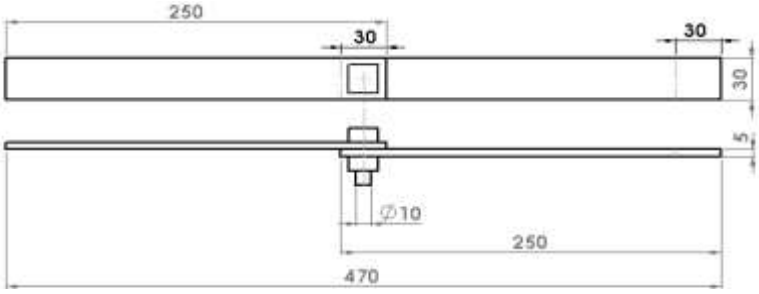


Fig. 3 Aluminium plate bolted joint dimensions

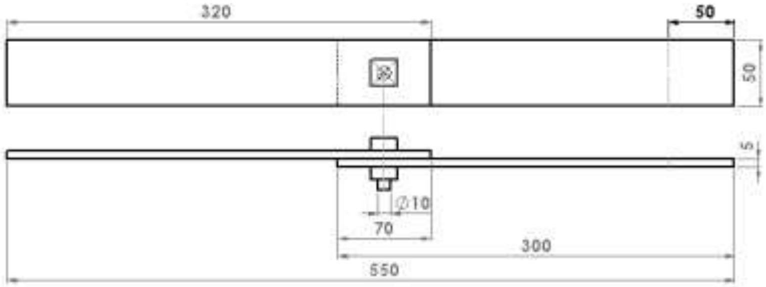


Fig. 4 Glass fiber plate bolted joint dimensions

3.4 Material properties

Table 1: Properties of materials used

Material	Properties of	
	Aluminium	Glass fiber
Density(Kg/m^3)	2700	2570
Poisson's Ratio	0.3	0.2
Ultimate tensile strength(MPa)	124	276
Yield Strength(MPa)	55	--
Modulus of elasticity(MPa)	69 X10^3	72X10^3

IV. EXPERIMENTAL ANALYSIS

Different cases according to objectives are considered as given below. Results obtained are given in tabular and graphical form wherever necessary.

Analysis is carried out considering different parameters like,

1. Material of plates
2. Configuration of joint
3. Use of anti-loosening devices like washer
4. Variation in preload

4.1Analysis of loosening behavior at different preload for straight aluminium bolted joint

Table 2: straight aluminium joint

	Natural Frequency(Hz)				
Preload (N)	**1st Mode**	**2nd Mode**	**3rd Mode**	**4th Mode**	**5th Mode**
2000	2	60	125.5	200	530.5
2500	1.8	62	118	120	400.5
3000	1.5	65.5	119	150	542

4.2 Analysis of loosening behavior at different preload for straight aluminium bolted joint with washer

Table 3: straight aluminium joint with washer

	Natural Frequency(Hz)				
Preload (N)	**1st Mode**	**2nd Mode**	**3rd Mode**	**4th Mode**	**5th Mode**
2000	2	75	115	132	400
2500	1.5	60.5	115.5	145	545
3000	1.5	50	113	160	434.5

4.3 Analysis of loosening behavior at different preload for perpendicular aluminium bolted joint without washer

Table 4: Perpendicular aluminium joint without washer

	Natural Frequency(Hz)				
Preload (N)	**1st Mode**	**2nd Mode**	**3rd Mode**	**4th Mode**	**5th Mode**
2000	1.5	62	130	139	340
2500	1.8	80	120	180.5	345
3000	1.6	65	130.5	200	360.5

4.4 Analysis of loosening behavior at different preload for perpendicular aluminium bolted joint with washer

Table 5: Perpendicular aluminium joint with washer

	Natural Frequency(Hz)				
Preload (N)	**1st Mode**	**2nd Mode**	**3rd Mode**	**4th Mode**	**5th Mode**
2000	1.7	55	135	145.5	335.5
2500	1.6	62	130	175	350
3000	1.5	60	125	170	345

4.5Analysis of loosening behavior at different preload for straight composite bolted joint without washer

Table 6: straight composite bolted joint without washer

	Natural Frequency(Hz)				
Preload (N)	**1st Mode**	**2nd Mode**	**3rd Mode**	**4th Mode**	**5th Mode**
2000	1.5	110.5	130	305	370
2500	1.6	110	120	250.5	560
3000	1.5	90	100	125	555

4.6 Analysis of loosening behavior at different preload for straight composite bolted joint with washer

Table 7: straight composite bolted joint with washer

	Natural Frequency(Hz)				
Preload (N)	**1st Mode**	**2nd Mode**	**3rd Mode**	**4th Mode**	**5th Mode**
2000	20	110	125	190	330
2500	2	15	110	130	335
3000	2	15	110.5	125	330.5

4.7Analysis of loosening behavior at different preload for perpendicular composite bolted joint without washer

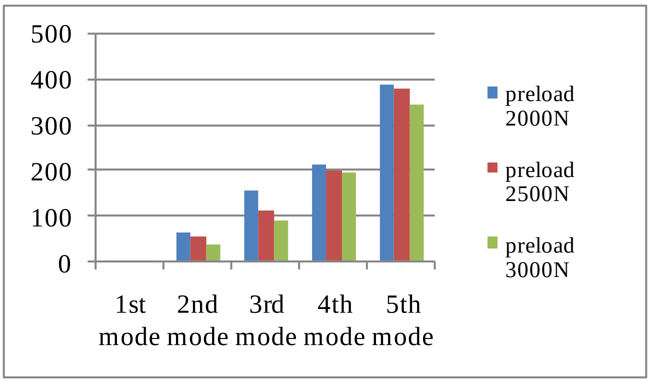
Table 8: Perpendicular composite bolted joint without washer

	Natural Frequency(Hz)				
Preload (N)	**1st Mode**	**2nd Mode**	**3rd Mode**	**4th Mode**	**5th Mode**
2000	1.5	65	155	215	390
2500	1.6	55	110	200	380.5
3000	1.5	35	90	195	360

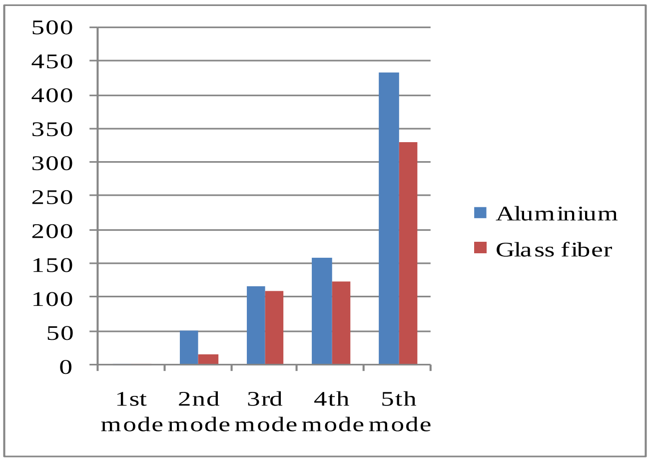
4.8Analysis of loosening behavior at different preload for perpendicular composite bolted joint with washer

Table 9: Perpendicular composite bolted joint with washer

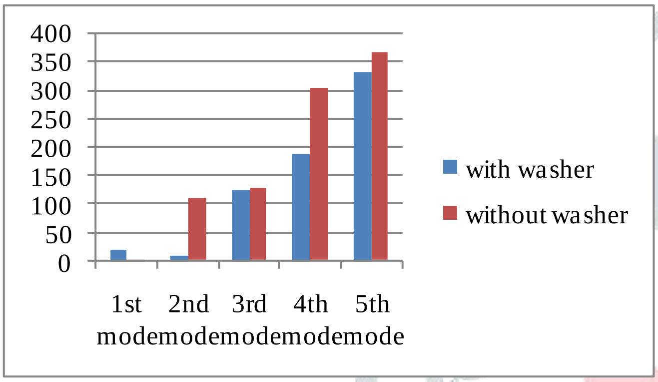
	Natural Frequency(Hz)				
Preload (N)	**1st Mode**	**2nd Mode**	**3rd Mode**	**4th Mode**	**5th Mode**
2000	1.6	60	160.5	200	388.5
2500	1.5	50.5	115	195	385
3000	1.4	30	85	190	340



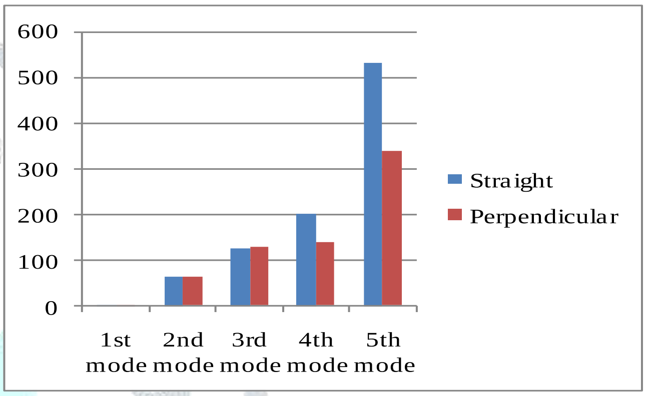
Graph 1: Variation of frequencies with preload



Graph 3: Variation of frequencies with material of joint



Graph 2: Variation of frequencies showing Effect of washer



Graph 4: Variation of frequencies with configuration of joint

V. FE ANALYSIS

Bolted joints shows nonlinear behavior which may arise due to material, geometry and dynamic properties of joints. Modal analysis determines the vibration characteristics such as natural frequency and mode shapes of a structure. Mode shape and natural frequency are the important parameters in the design of a structure subjected to dynamic loading. Also modal analysis serves as the starting point for another more detailed dynamic analysis. Therefore it is crucial to check the natural frequency of the structure while doing transient or dynamic numerical analysis but there is a big drawback in predicting the bolted joint response using numerical methods. Among all the numerical methods, Finite Element Analysis is commonly used for pre-stressed modal analysis.

Non-Linear commercial FE code ANSYS 15.0 is used to simulate the impact analysis on the cantilever beam with bolted lap joint. Pre-stressed modal analysis is solved using mechanical APDL solver.

Realistic and practical considerations are taken into account to get reliable results.

5.1. Model development, Contact conditions and Meshing

5.1. 1Model Development

Different components Plate-1, Plate-2, Washer, Bolt and Nut are modeled in solid works 2013 and assembled as shown in Figure. It is imported into ANSYS Workbench for FEA

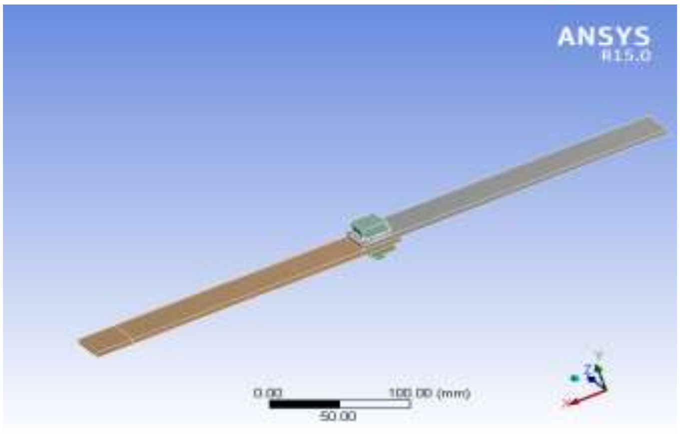


Fig. 5 Imported model in Ansys 15.0

5.1.2 Contact conditions

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 10.

Table 10. Contact conditions applied in geometry

Sr. No	Contact	Target	Type of Interaction	Coefficient of Friction	Formulation
1	Nut	Plate-1	Frictional	0.15	Augmented Lagrange
2	Bolt	Nut	No-separation	-----	MPC
3	Washer	Plate-2	Frictional	0.15	Augmented Lagrange
4	Bolt	Washer	Frictional	0.15	Augmented Lagrange
5	Plate-2	Plate-1	Frictional	0.15	Augmented Lagrange

5.1.3 Meshing & Boundary condtions

Formulation of elements in Finite element analysis is an important factor that can influence the simulation results considerably. All components of cantilever beam are meshed using tetrahedron method with type having mesh size 3mm with fine relevance and span angle center as shown in Figure

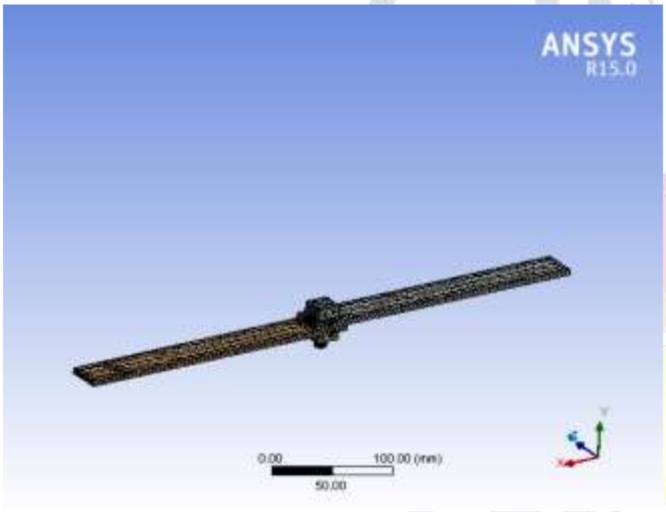


Fig. 6 Meshing applied to solid model

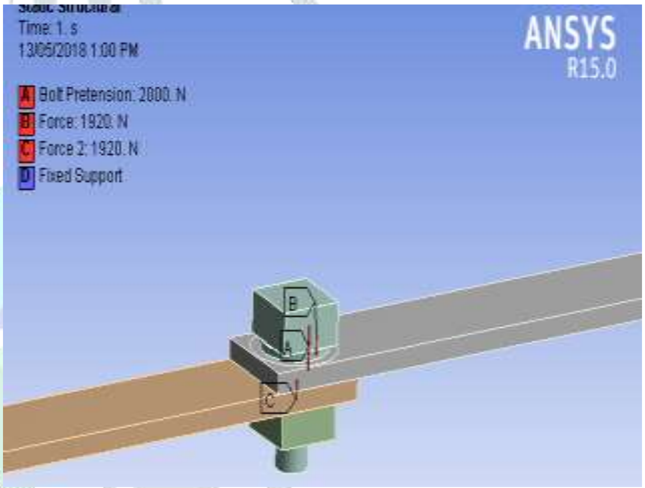


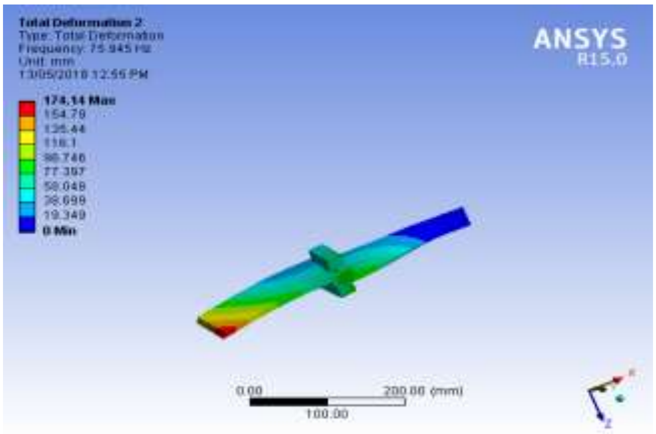
Fig. 7 Boundary conditions applied to solid model

VI. SIMULATION OF EXPERIMENTAL RESULTS WITH FEA

Modal analysis serves as the starting point for another more detailed dynamic analysis. 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 mode shapes and their natural frequency of vibration while doing transient or dynamic FE analysis. Therefore the first step in FEA is the comparison between results by experimental and Finite Element Analysis.

Five Mode shapes are obtained for each preload condition and corresponding natural frequencies are simulated with experimental frequencies.

Comparison of mode shapes can be used to predict failure and loosening area of bolted joint.



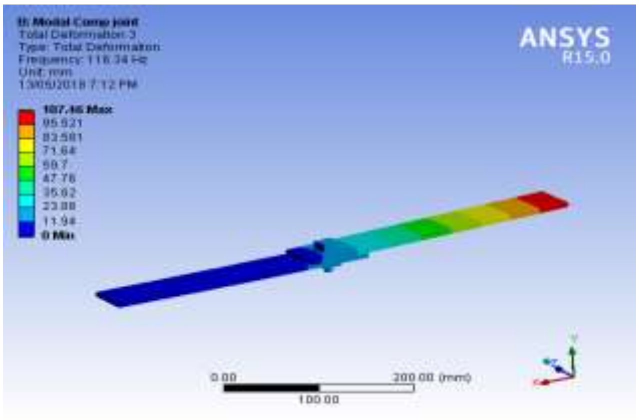


Fig. 8 2nd mode shape showing little twist

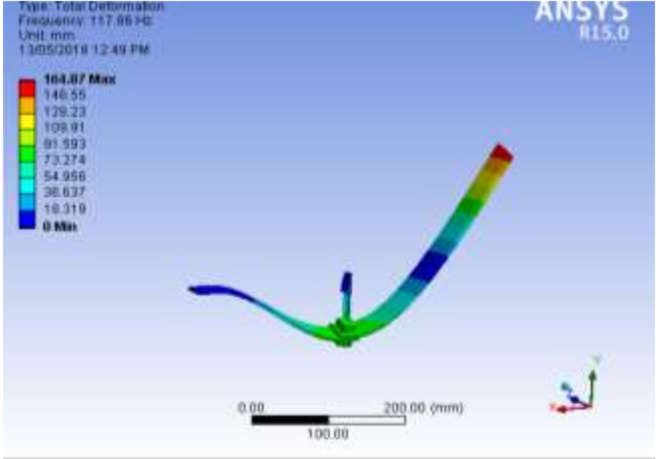


Fig. 9 3rd mode shape with bending

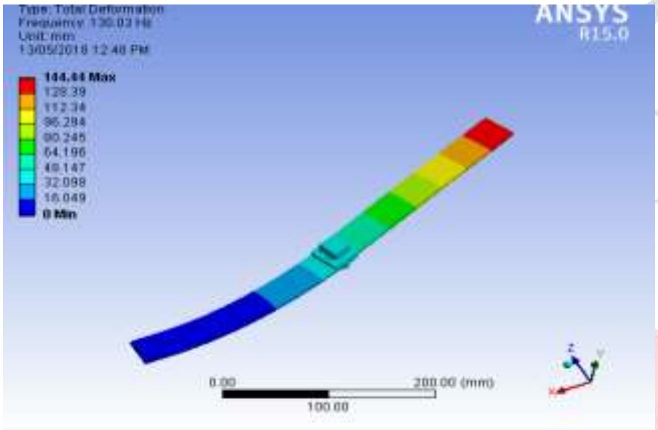


Fig. 10 4th mode shape start of loosening

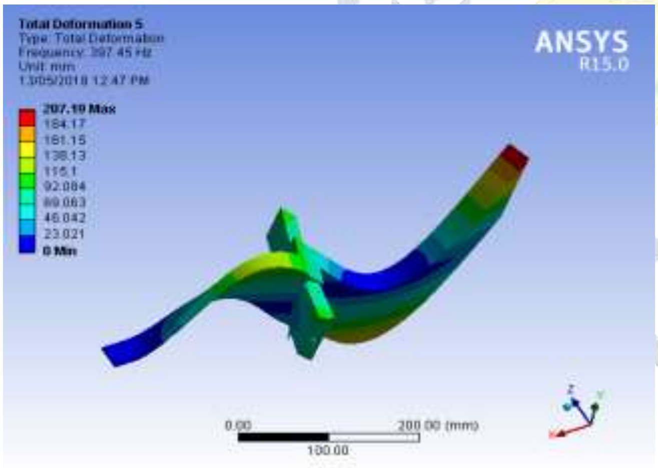


Fig. 11 5th mode shape more loosening and twist

6.2Composite material joint

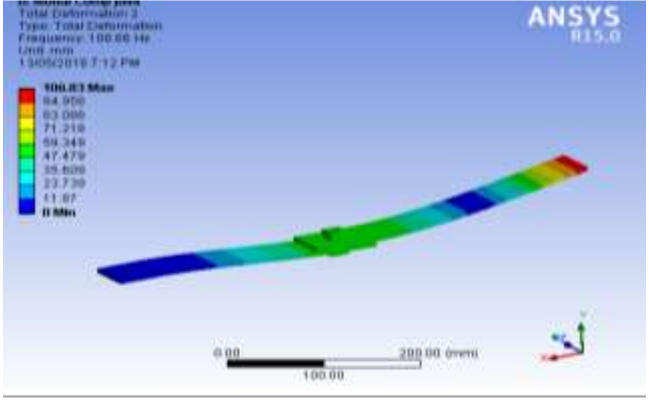


Fig. 13 3rd mode shape

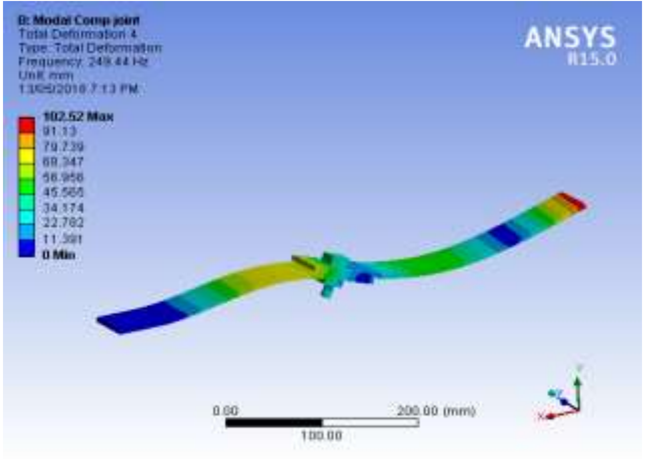


Fig. 14 4th mode shape showing bend

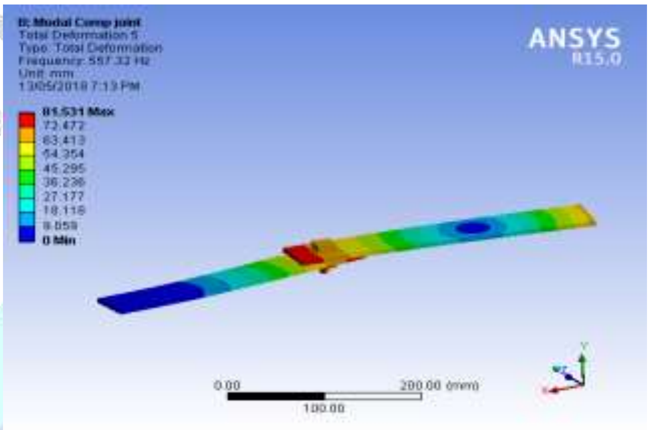


Fig. 15 5th mode shape showing loosening

6.3Perpendicular joint

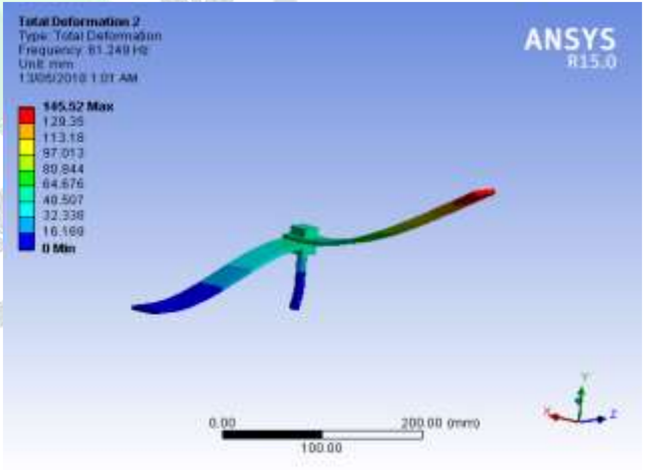


Fig. 16 2nd mode shape showing bending

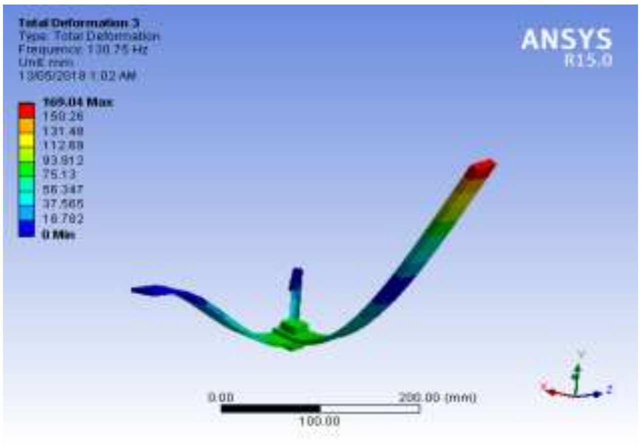


Fig. 12 2nd mode shape showing bending

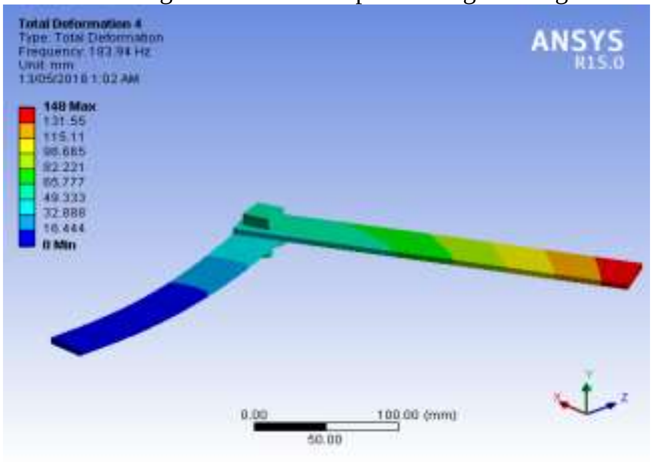


Fig. 18 4th mode shape showing bend

Fig. 17 3rd mode shape showing bending

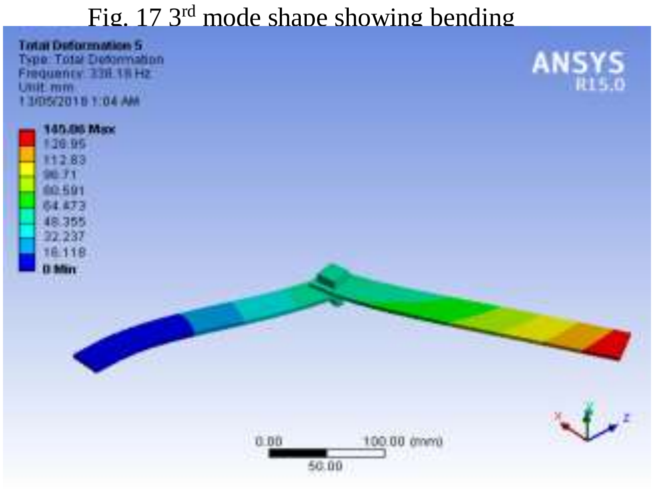


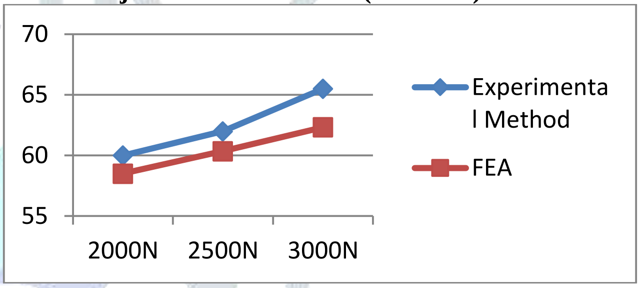
Fig. 19 5th mode shape showing loosening

VII. VALIDATION OF RESULTS

Results obtained by experimental method and FEA method are compared and validated as given below.

7.1Aluminium joint without washer (2nd mode)

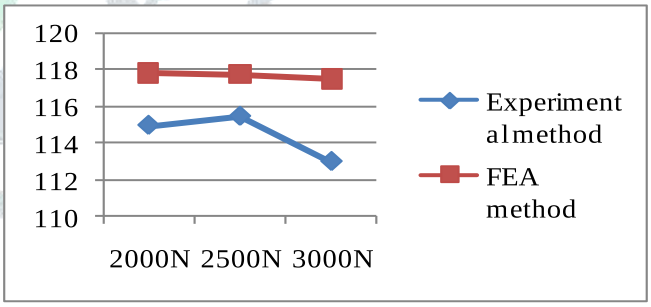
Preload (N)	Natural frequency (Hz)using	
	Experimental method	FEA method
2000	60	58.50
2500	62	60.35
3000	65.5	62.33



Graph 5: Comparison of experimental and FEA results

7.2 Aluminium joint with washer (3rd mode)

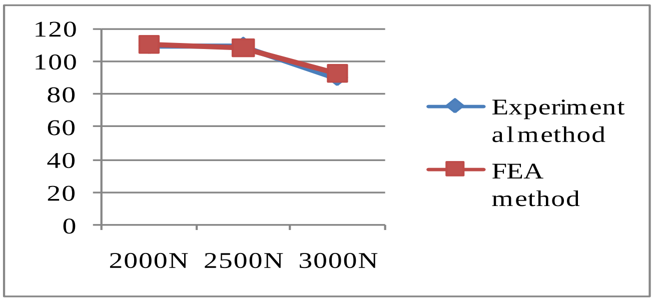
Preload (N)	Natural frequency (Hz)using	
	Experimental method	FEA method
2000	115	117.86
2500	115.5	117.79
3000	113	117.54



Graph 6: Comparison of experimental and FEA results

7.3 Glass fiber joint without washer (2nd mode)

Preload (N)	Natural frequency (Hz)using	
	Experimental method	FEA method
2000	110.5	110.73
2500	110	108.66
3000	90	93.7



Graph 7 : Comparison of experimental and FEA results

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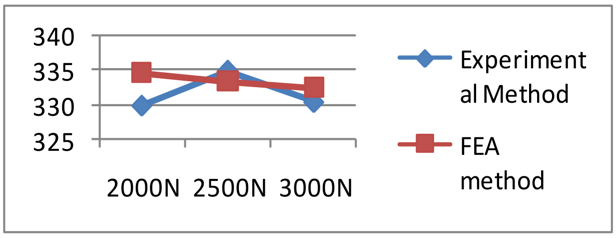
7.4Glass fiber joint with washer (5th mode)

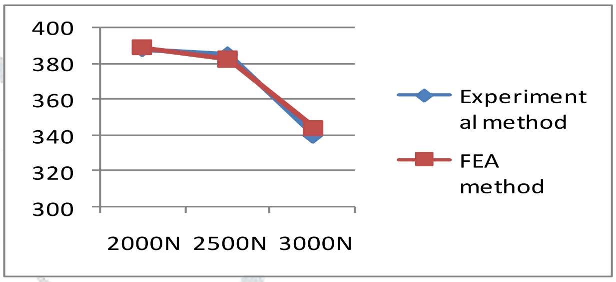
Preload (N)	Natural frequency (Hz)using	
	Experimental method	FEA method
2000	330	334.65
2500	335	333.48
3000	330.5	332.53



Graph 8: Comparison of experimental and FEA results

7.5 Perpendicular joint with washer (5th mode)

Preload (N)	Natural frequency (Hz)using	
	Experimental method	FEA method
2000	388.5	388.67
2500	385	382.12
3000	340	344.41



Graph 9: Comparison of experimental and FEA results

Similarly results are simulated for other cases; little error in reading may be due to variation in intensity of impact and calibration.

VIII. CONCLUSIONS

1. Vibration based method that uses change in natural frequencies is an effective method for analyzing the loosening behavior of bolted joints under low velocity impact loading.
2. We have observed that in general, loosening starts with increase in natural frequency and it can be observed especially in 4th and 5th mode shape.
3. Loosening between fastened components increases with decreasing preload on bolt and nut of bolted joint linearly.
4. Loosening behavior of bolted structure depends upon material stiffness of fastened plates when it is made up of same material but in hybrid joint loosening of bolted structure depends upon material property of fastened plate at which impact is done
5. Loosening behavior of single lap cantilever type bolted joint depends upon the magnitude of impact load and preload applied and region on structure at which impact is done.
6. With use of washer in joint, as frequency of vibration is less, it can be concluded that bolted joint with washer is less prone to Loosening.
7. Washer provides more stiffness to the joint in comparison with normal joint.
8. Stiffness of bolted structure reduce drastically when hole clearance increases above standard hole clearance for respective bolt size.
9. Probability of loosening is less in perpendicular joint configuration than straight joint.
10. Glass fiber nut bolts require less tightening torque but they can hold plates stiffly, hence can be used effectively in certain applications where weight reduction is necessary.

IX. FUTURE SCOPE & NEED

There is probability of loosening & failure due to vibrations in bolted joints which are used in different structures and machines, hence this study is always necessary to avoid premature failures in bolted joints.

The above work can be used to predict loosening & failure of bolted joint under low velocity impact loading.

Composite material nut bolts (Carbon and glass fiber nut bolts) can be tested for loosening under vibration in different applications and different thread diameters.

Better composite material for nut bolts can be developed using glass fiber, carbon fiber & polymers to get lesser weight and lesser cost.

The same approach and analysis can be followed for compound cantilever beam.

X. REFERENCES

[1]ZhenZang, Mengbing Liu, Zang king Su, Yi Xiao, 2017, “Continuous Monitoring of Residual Torque of Loose Bolt in A Bolted Joint”, Science Direct, Procedia Engineering 188 (2017) pp.278 – 285

[2] P. Langer, A. Hoppe, C. Guist, S. Marburg), 2017, “Bolted Joints: Eigen frequencies from non-linear FE-models and experimental modal analysis”, Research Gate, September 2017, pp. 5431-5441

[3]Jianhua Liu, Hua jiang Ouyang, Zhiqiang Feng, Zhenbing Cai, Xuetong Liu, Minhao Zhu,2017,“Study on self-loosening of bolted joints excited by dynamic axial load”,Tribology International, May 2017,pp.1-34

[4]Jianhua Liu , Hua jiang Ouyang , JinfangPeng ,Chaoqian Zhang Pingyu Zhou,Lijun Mac, Minhao Zhuan,2016, “Experimental and numerical studies of bolted joints subjected to axial excitation”, Elsevier ,Wear 2016,pp.66-77

[5]ShriramDravid,KarthikeyaTripathi,ManojChoukse,2014, “Role of Washers in Controlling loosening of Full Threaded BoltedJoints” Science Direct, Procedia technology,pp.543-552

[6]Feblil Huda, ItsuroKajiwara, Naoki Hosoya, Shozo Kawamura,2013“Bolt loosening analysis and diagnosis by non-contact laser excitation vibration tests”, Science direct, Mechanical Ssytems & signal processing,2013,pp.589-604,

[7] Ravinder Kumar, “Causes & prevention of loosening in pre stressed bolts”, 2013, mechanica Confab

[8]Olfa Ksentini, Bertrand Combes, Mohammad Salim Abbes, Alain Daidie,2013,“Behavior of Single-Lap Bolted Joint Subjected to Dynamic Transverse Load”,2013 Springer-Verlag Berlin Heidelberg

[9] Naoya Nishimura, Katsuhiko Murase, Toshio Hattori, Takeru Watanabe,2013, “Loosening Evaluation of Bolt-Nut Fastener Under Transverse Cyclic Loading”, Polish Academy of Sciences, Engineering Transactions,2013,pp.151-160

[10] G. Dinger , C. Friedrich 2011, “Avoiding self-loosening failure of bolted joints with numerical assessment of local contact state”, Science direct, Engineering Failure Analysis 18 (2011) pp.2188–2200

[11]Anirban Bhattacharya, AvjitSen, Santanu Das,2010, “An investigation on the anti-loosening characteristics of threaded fasteners under vibratory conditions” Science direct, Mechanism and Machine Theory 45 (2010),pp. 1215–1225

[12]Loosening & sliding behavior of nut bolt fastener under transverse loading (Toshio Hattori, Minoru Yamashita, Hiroki Mizono , Tomohiro Naruse),2010, EDP Sciences

[13]Parametric study of threaded fastener loosening due to cyclic transverse loads J.A. Sanclemente, D.P. Hess, 2007,Science direct

[14]Influence of fastener placement on vibration-induced loosening (N.G. Pai, D.P. Hess), 2003, Science direct

[15]’Modal Analysis of rectangular plate with lap joints to find natural frequencies & mode shapes’, M. Bhusnar, S. S. Sarawade, 2016, IOSRJMCE

[16] Kumarswamy Karpanan Nakalswamy, Experimental and numerical analysis of structures with bolted joints subjected to impact load. [PhD thesis],Las Vegas: University of Nevada; 2010