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Development of Test Rig for Behaviour Study of Metal to Composite Bolted Joint under Combined Bending and Vibration Loading

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Abstract: Testing is very crucial to ensure the effectiveness of any component. The current scenario only focuses on the cases of uniaxial loading while in real life situations, the components are subjected to multiple loads simultaneously. In such cases conventional testing doesn't help to predict the exact behaviour of component in real life applications. To study correct behaviour, it is important to adopt the approach of testing under combined loading. Use of composite materials in various industrial sectors is increasing day by day due its desirable properties. Due to the extensive use of composites, it is necessary to study behaviour of composites under combined loading. This paper primarily focuses on development of a test rig for the study of behaviour of composite subjected to combined loading. The combined loading constitutes primary load vibration and the secondary load consists of bending. Also, the paper focuses on identifying the effect of various parameters like load, frequency, and amplitude on the behaviour of composite material.
Keywords: Behaviour study, bending, Carbon fibre, combined loading, vibration.

I. INTRODUCTION

A composite is a structural material that consists of or more combined constituents that are combined at a macroscopic level and are not soluble in each other. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix. The reinforcing phase material may be in the form of fibres, particles, or flakes. The matrix phase materials are generally continuous. Examples of composite systems include concrete reinforced with steel and epoxy reinforced with graphite fibres, etc. [1].

Monolithic metal and their alloys do not always fulfil the demand in some special applications such as Space shuttles, Aeroplane, marine vehicles, etc. Composites can be designed in such a way that it will complete the requirement of a particular application specifically.

From Figure 1 it can be concluded that the composite materials offer higher strength to weight ratio than metals. Composites offer several other advantages over conventional materials. These may include improved strength, stiffness, fatigue and impact resistance, thermal conductivity, corrosion resistance, etc. Due to these desirable properties, composite materials are becoming popular these days in industries like automation, aviation, robotics, automobile, etc.

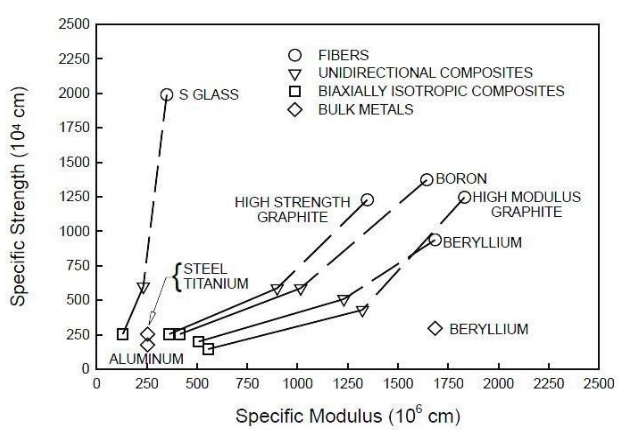

Figure 1 Relationship between Specific strength and Specific Modulus for Different Material [2]

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In the current scenario, only the unidirectional testing approach is considered for the composite but the conditions have arrived which requires a combined loading approach in such cases conventional testing may not fulfil the required results. In real-life applications, various combination of loads acts on components simultaneously. For example, Thermal and Bending load, Vibration and bending load, etc. In this paper, a setup is developed in order to simulate loading condition of an automotive rear car spoiler. A car rear spoiler is subjected to two primary loads, one is bending due to the drag force developed because of air and other is vibration due to excitation from road surface irregularities.

Figure 2 Automotive rear car spoiler [2]

This paper primarily focuses on development of test rig to simulate real life loading case and studying the effect of the combined loading on the behaviour of composite material.

Therefore, the objectives of this research paper are to design and develop a test set up for behaviour study of metal to composite bolted joint under combined bending and vibrations. To simulate load case as that of automotive rear spoiler and to test the metal to composite bolted joint specimen based on DOE and to determine the influence of parameters namely load, frequency and amplitude on behaviour of metal to composite bolted joint.

II. LITRATURE REVIEW.

In In the current scenario, only the unidirectional testing approach is considered for the composite testing, but conditions have arrived which requires a combined loading approach in such cases conventional testing may not fulfil the required results.

Following is the work done by scholars:

Fatih Kagnici have investigated Vibration Induced Fatigue Assessment in Vehicle Development Process. In this study a new methodology was developed in order to predict the fatigue damage of vehicle and compared with the conventional method which is used frequently in automotive sector. [3]

Rym Taktak, Noamen Guermazil and Tasnim Kossentini Kallel have carried out experimentation whose main goals was to investigate comparison of the mechanical behaviour of resins reinforced with different woven fabrics (bidirectional and quadriaxial rovings), manufactured with the classical hand lay- up process. The quadriaxial composites (QA/VE and QA/UP) with stacking sequences of [0°, +45°, 90°, −45°] can bear the stress of about 75 MPa steadily, when subjected to tensile loading, and show balanced performance. [4]

Kakur Naresh, Shankar Krishnapillai and Velmurugan Ramachandran have studied the tensile and impact properties by performing a series of tests on neat epoxy and different stacking sequences of UD CFRP composites. [5]

Zhengwei Fan, Yu Jiang, Shufeng Zhang and Xun Chen have carried out vibration testing on a Carbon fibre composite in order to study the effect of holes and notches on fatigue life using electrodynamic shaker. [6]

N. B. V. Lakshmi Kumaria, Dr.Afroz Mehar b, Mohammed Abdulrahmanc, Sheetal Tatinenid , Ellendula Venkateshwara Shashanke and Jonathan Ted Muthyalaf concluded that the material used for the composite laminate is Carbon Epoxy, The orientation of the 10 ply composite is [90° , 0°, -45°, 45°]s. The result obtained after calculating using MATLAB and comparing with the already obtained values are found to be within the limit. [7]

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III. TEST SETUP.

The test setup consists of two parts as follows:

A. Electrodynamic Shaker

For application of vibration load to the specimen a "Electrodynamic Shaker" is used. The electrodynamic shaker functions to deliver a force proportional to the current applied to its voice coil. These devices are used in such diverse activities as product evaluation, stress screening, squeak-and- rattle testing and modal analysis. These shakers may be driven by sinusoidal, random or transient signals based upon the application. They are invariably driven by an audio frequency power amplifier and may be used "open loop" (as in most modal testing) or under closed-loop control where the input to the driving amplifier is servo-controlled to achieve a desired motion level in the article under test. The heart of the shaker is a single-layer coil of wire, suspended in a radial magnetic field. When a current is passed through this coil, a longitudinal force is produced in proportion to the current and this is transmitted to a table structure to which the test article may be fixed.

Specifications of the shaker used are as follows:
Model: SEV 125 – DSA 1K
Dimensions: 540 x 375 x 495 (mm) Peak Displacement: 20 mm
The types of tests available on the electrodynamic shaker are as follows:

1) Swept Sine Test
2) Random Test
3) Shock Test

Figure 3 Electrodynamic Shaker

For this experimentation Swept Sine Test is to be used. In practice the frequency is swept back and forth between a lower limit and an upper limit at a pre- determined rate; the rate may be specified as linear, logarithmic, or stepped.

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B. Bending Load Attachment

For application of bending load, a separate attachment is manufactured. The components of the bending attachment are as follows:

1) *Frame:* Frame is designed considering space requirement and then it is validated using ANSYS. For the fabrication of the frame, square and rectangular tubes are used in order to reduce overall weight of the attachment. To increase the strength of beams in the frame, two rectangular tubes are welded together and then used as a single entity. Rubber pads are introduced in between main frame and sub frame's bolting section so that the vibration in the frame gets damped reducing error in experimentation.

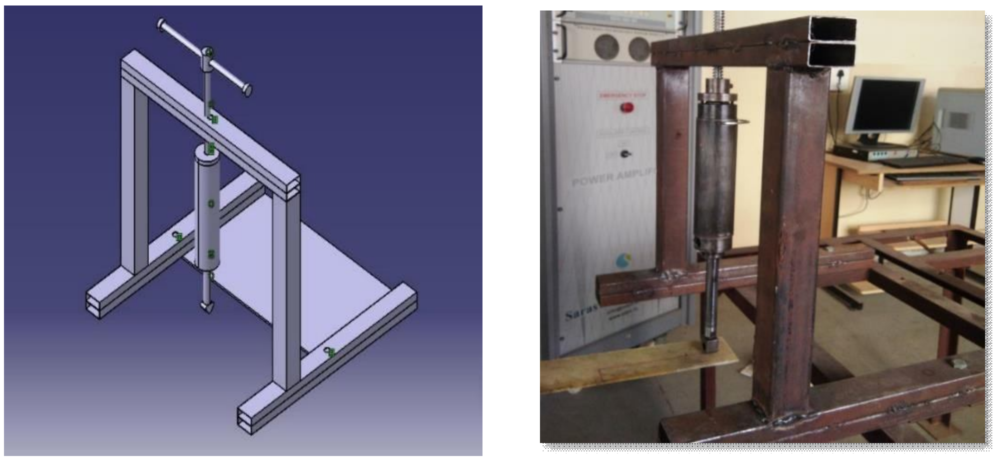

Figure 4 CAD model and fabricated frame

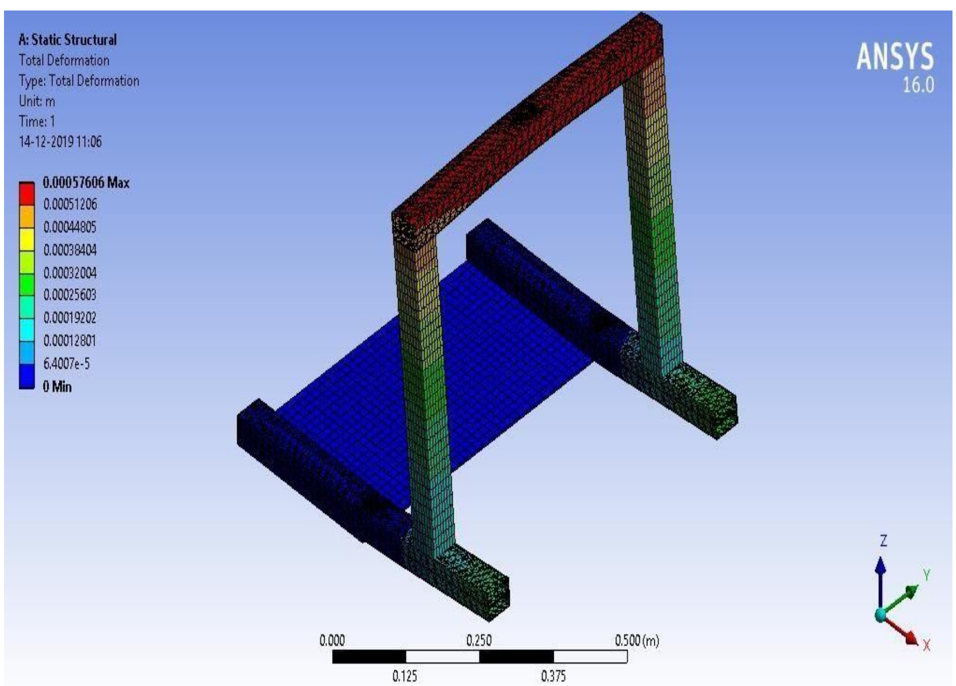

Figure 5 FEA analysis of frame

The frame is subjected to a load of 1000 N for Finite Element Analysis, the results can be summarized as follows:
The total deflection observed is 0.57 mm and maximum deflection at free end is 0.3 mm. Maximum stress induced is 139.18Pa. Overall Factor of safety achieved is 1.8. This confirms safety of frame.

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2) *Loading Arrangement:* The loading arrangement consists of a square threaded screw and nut, actuator assembly. The arrangement is as shown in Figure 7.

The material requirement of the actuator assembly is as shown in Table I.

Table I
Material requirement of actuator assembly

	Name	Material	Size	Length	No
1	Spring	C65	D1 = 45mm Nt = 12, D = 5 mm	150 mm	1
2	Nut	CuSn10Zn2	M16	22 mm	1
3	Screw	C50	M 16	450 mm	1

Horizontal supports have been added for the actuator so that it prevents the wobble of loading arrangement.
In the loading arrangement as shown in Figure 6, the load applicator is directly bolted to the specimen in order to avoid slipping while simultaneous application of vibration and bending load

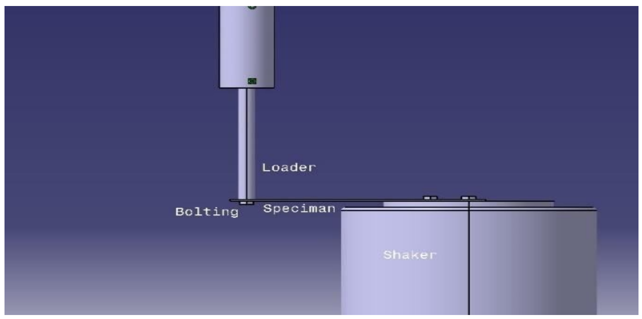

Figure 6 Loading arrangement

C. Specimen

1) *Specimen Size:* Standard test methods mentioned in D790 cover the determination of flexural properties of unreinforced and reinforced plastics, including high-modulus composites and electrical insulating materials in the form of rectangular bars moulded directly or cut from sheets, plates, or moulded shapes. These test methods are generally applicable to both rigid and semirigid materials. For high-strength Reinforced Composites, the span-to- depth ratio shall be chosen such that failure occurs in the outer fibres of the specimens and is due only to the bending moment. A span-to-depth ratio larger than 16:1 may be necessary (32:1 or 40:1 is recommended). For some highly anisotropic composites, shear deformation can significantly influence modulus measurements, even at span-to-depth ratios as high as 40:1. Hence, for these materials, an increase in the span-to- depth ratio to 60:1 is recommended.

According to these standards selecting specimen size as 300 mm * 75 mm * 3 mm

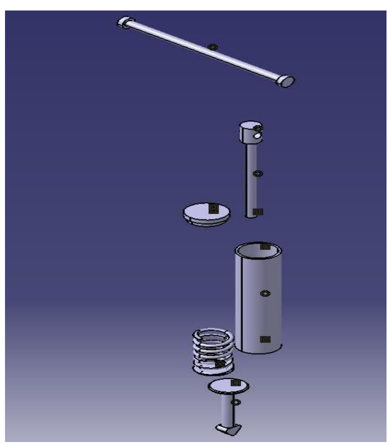
Figure 7 Exploded view of actuator assembly

2) *Specimen Material:* Carbon fibre have remarkable properties such as tensile strength, stiffness, low density, electrical conductivity, and chemical inertness. Carbon fibres have been used to manufacture sports cars as well as sports equipment. Currently, a great deal of attention is being paid to reduce the weight of passenger vehicles to increase vehicle fuel economy and lower the greenhouse gas emissions. Thus, carbon fibres are now used in aircraft and industrial applications such as pressure vessels, windmills, civil engineering/construction-related uses, and cars and yachts. [3]

Carbon fibre composites are ideally suited to applications in which strength, stiffness, low weight, and outstanding fatigue characteristics are critical requirements. [3]

Taking into consideration the needs of modern industrialization 'Carbon fibre Composite' is selected as a specimen material.

Table II
Carbon Fibre Specifications

Characteristics	Specifications	Tolerances
Area Weight (g/m^2)	400	± 3%
Width (mm)	500	-0 / + 10 mm
Dry Fabric Thickness (mm)	0.43	± 0.03 mm

Table III Fibre Properties

Property	Value
Density (g/cm^3)	1.8
Filament Diameter (µm)	7
Tensile Strength (MPa)	4000
Tensile Modulus (GPa)	240
Elongation (%)	1.7
Sizing	Epoxy Compatible

3) *Selection Of Laminate Orientation:* Laminated composite materials consist of layers of at least two different materials that are bonded together. Lamination is used to combine the best aspects of a constituent layers and bonding material in order to achieve a more useful material. One of the fundamental advantages of laminates is their ability to adapt and control the orientation of fibres to best resist loadings. Plies contribute to the laminate resistance by orienting with respect to the loading direction. fibres oriented at 45° can support the tension and –45° can support compression. [7]

The composites with stacking sequences of [0°, +45°,

−45°,90°] can bear the maximum load with minimum deflection hence this laminate orientation is popular among automotive manufacturers. [4]

Taking into account the advantages and popularity, selecting orientation as symmetric [0°, +45°, −45°,90°].

1 Ply = 0.127 mm

1 Laminate = 8*0.127 = 1.016 mm

Total Specimen thickness = 3*1.016 = 3.048 mm Therefore, Area of specimen = 300 * 75

$= 22500\ mm^2$

$= 0.0225\ m^2$

Figure 8 shows actual manufactured test setup with specimen attached.

Figure 8 Fabricated test setup

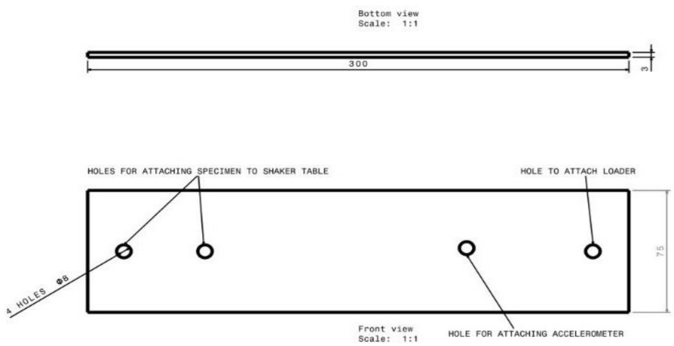

Figure 9 Specimen drawing

IV. TESTING PARAMETERS

Following are the various parameters to be considered for the experimentation.

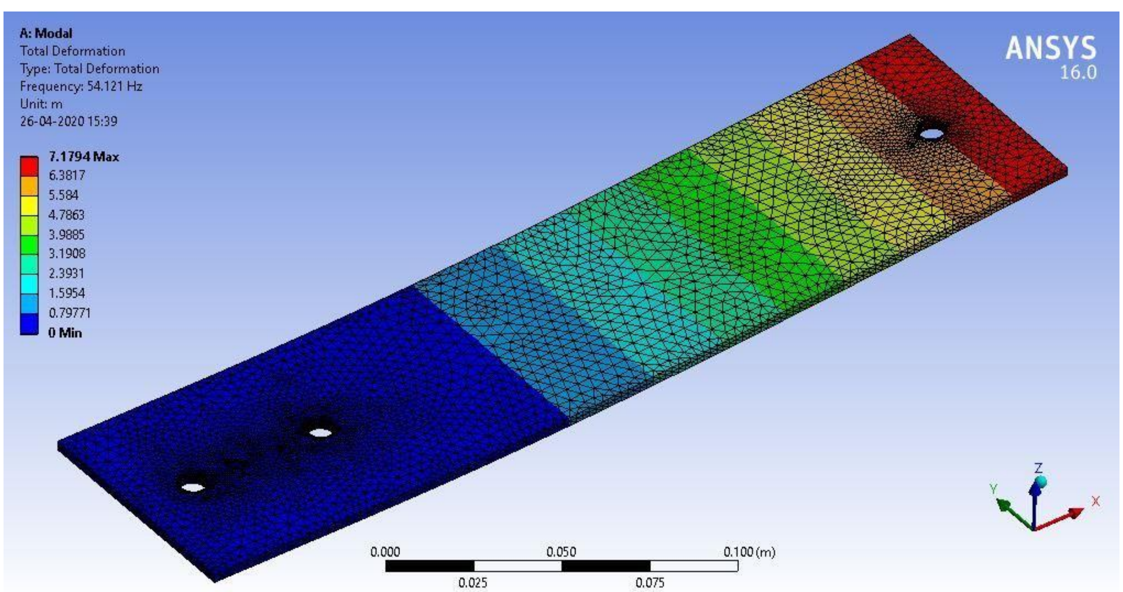

Figure 10 Modal analysis of specimen in ANSYS

A. Load Variation

The tensile strength of the carbon fibre composite with given compositions is 307 MPa. [5]

For selecting the reference loads let us consider three load steps till the carbon fibre composite specimen reaches its ultimate strength. For the selected dimension of specimen, the stress calculations are as follows:

Calculations are as follows:

$\sigma_b = M/Z$ M = Load*Distance = 180*P

For a rectangular section,

$Z = b*d^2/6 = 75*3^2/6 = 112.5\ mm^3$

$\sigma_b = (180*P)/112.5$ $\sigma_b = 1.6*P$

Therefore, P **= $\boldsymbol{\sigma_b}$ / 1.6**

So, for calculating the reference load values, we have to select 3 values of Bending stress till it reaches ultimate strength of the carbon fibre composite. To calculate the intermediate stress value using geometric progression,

$\sigma_1 = 50$ Mpa $\sigma_3 = 307$ Mpa

Geometric Progression Ratio = $\Phi = (307/50)^{0.5} = 2.4779$

$\sigma_2 = \Phi * \sigma_1 = 2.4779*50 = 123.895$ MPa

Therefore, the reference loads are selected as follows: $P_1 = 50/1.6 = 31.25$ N

$P_2 = 123.895/1.6 = 77.43$ N

$P_3 = 307/1.6 = 191.875$ N

B. Frequency Variation

In order to evaluate the natural frequency of specimen for deciding frequency parameter for testing, modal analysis of specimen is carried out using ANSYS.

For analysis purpose the material of specimen selected in ANSYS is “Epoxy Carbon Woven 230GPa Wet”.

From the results it is clear that the natural frequency of the specimen is 54.12 Hz.

In order to check the behavior of carbon fiber composite specimen at resonant frequency selecting one of the frequency variations for testing as 60 Hz.

The frequency variation is taken as a bandwidth to carry out the swept sine test. E.g. 3 Hz to 60 Hz. This is done in order to identify the change in natural frequency of the specimen in various loading combinations as discussed before.

The frequency variation bandwidth is started from 3 Hz instead of 1 Hz that is to eliminate testing errors.

From the observation of pilot experimentation, the specimen under combined loading started vibrating abruptly around 40 Hz. To verify this another frequency variation is decided to be 40 Hz.

Hence the frequency variations are finalized as: F1 = 40 Hz

F2 = 60 Hz

C. Amplitude Variation

The electrodynamic shaker has the facility to decide the amplitude of induced vibrations through shaker table. So, taking into consideration some real-life applications of composites, following are the amplitude variations decided:

A1 = 2 mm (Vehicle on plane road)

A2 = 5 mm (Vehicle on Off-road conditions) A3 = 10 mm (All-terrain vehicle)

V. TESTING AND RESULTS

Sample experimentations are carried out using Glass Fibre composite and Carbon Fibre composite. This experimentation is carried out by subjecting the specimen to combined loading.

As shown in Figure 12 there is no sign of resonant frequency. This is due to the wrong position of accelerometer (i.e. At the end of specimen). To rectify this issue the most feasible solution is found out to be shifting the position of accelerometer to the centre of specimen along the length.

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Result from experimentation on Glass fibre composite is as shown in Figure 13. From the graph it is observed that the peak displacement is at 6 Hz which indicates resonant frequency of Glass fibre specimen.
Similarly, in case of Carbon fibre specimen peak displacement will indicate resonant frequency.

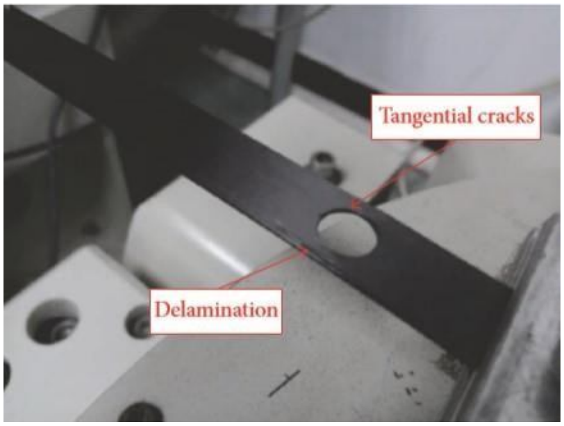

Figure 11 Delamination phenomenon [6]

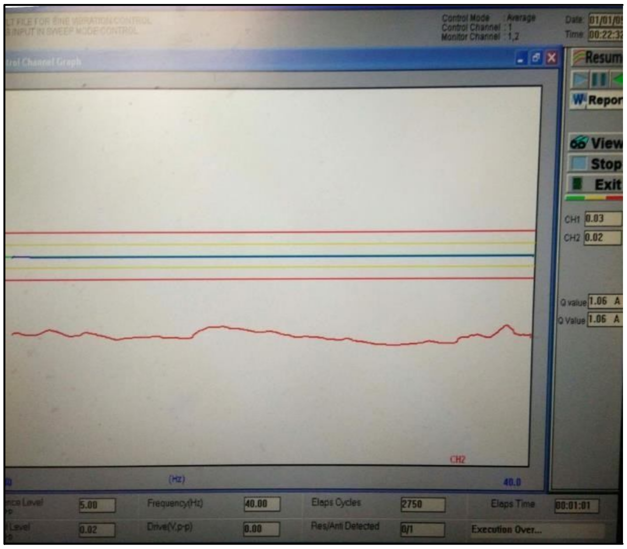

Figure 12 Displacement Vs Frequency graph for combined loading on Carbon fibre specimen

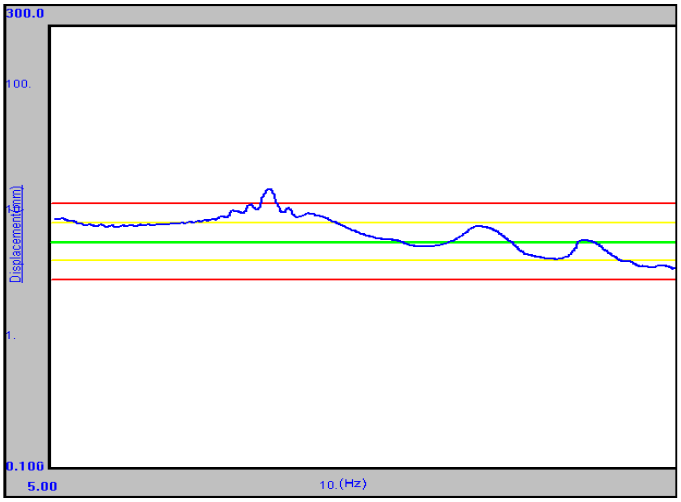

Figure 13 Displacement Vs Frequency graph for vibration loading on Glass Fibre specimen

VI. CONCLUDING REMARK

From the literature studied and sample experimentation following are the concluding remarks:

The sample test was carried out successfully, which indicates that the test rig developed for applying vibration and bending load simultaneously is working properly. Vibrations from the specimen are not transferred to frame due to presence of rubber pads in between main frame and sub frame. In order to ensure the proper working of electrodynamic shaker it is necessary to select the starting frequency as 3 Hz. This limits time required to initiate the test and reduces testing errors. After carrying out the complete test, none of the components of test rig have failed. This verifies that the design of the test rig is safe.

As the testing is continued for prolonged period of time it is observed that the composite specimen undergoes microscopic cracks and delamination. As a result, the natural frequency of specimen decreases as damage to the specimen increases. A cross ply specimen initially experiences tangential cracks along the surface then eventually leads to delamination damage. The microscopic crack propagation is initiated from small holes created due to manufacturing defect present on specimen surface. The peak frequency decreases to a certain degree initially then remains constant till delamination phenomenon. The first decrease in frequency is considered to be the life of specimen.

With some modification in the frame, it can be used to apply bending load at various sections of specimen. Also, by carrying out experimentation using electrodynamic shaker, change in natural frequency of test specimen with and without bending load can be computed.

VII. ACKNOWLEDGMENT

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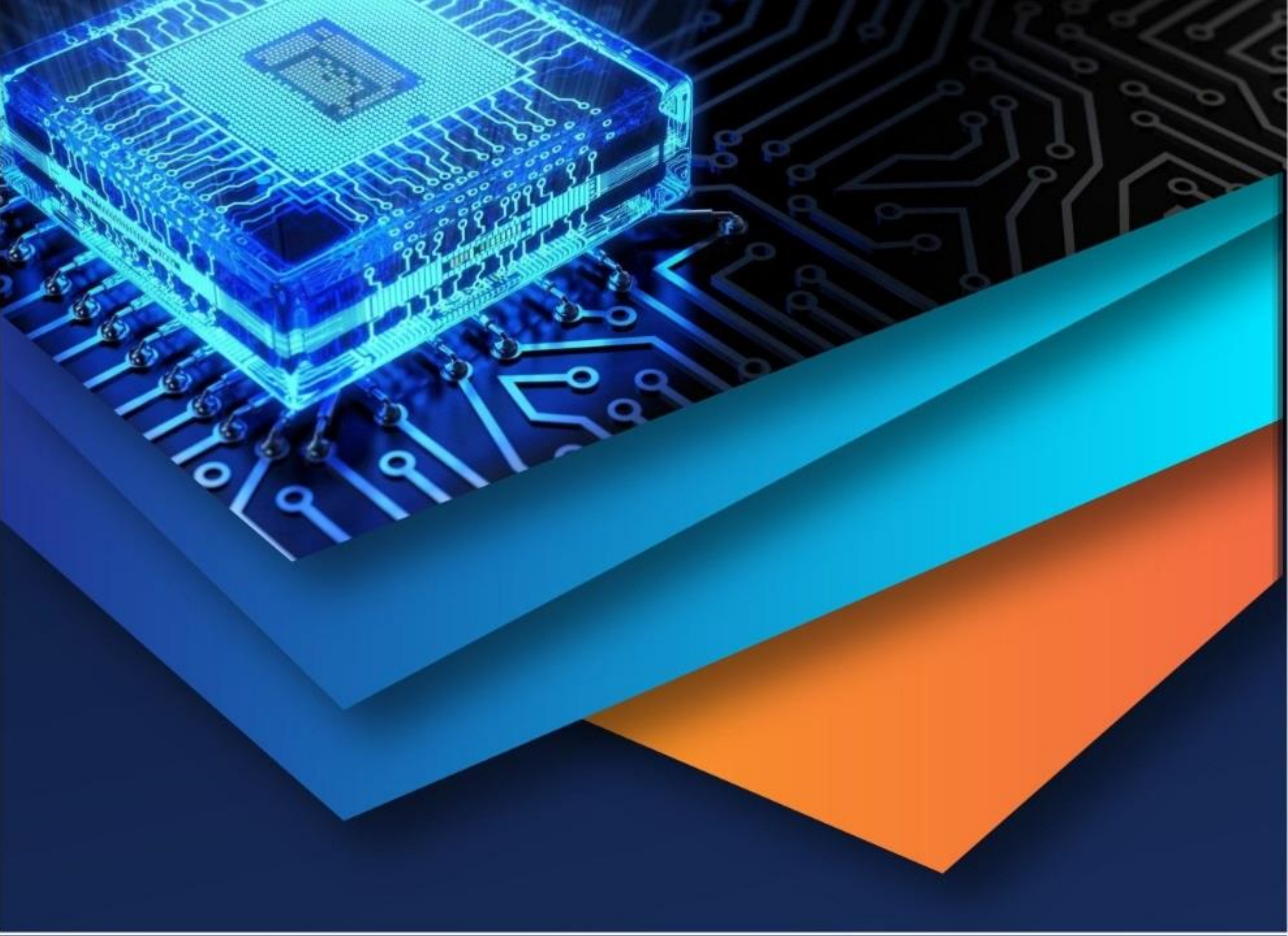

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