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Study on Effect of Vibration Loading of Beam Specimens on its Dynamic Characteristics

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Abstract

Vibration fatigue is an important aspect to be considered during the design and development of any structure or component operating under vibration environment. Any component under fatigue may fail abruptly below the yield or ultimate point, if it reaches its end of fatigue life. Hence fatigue life estimation is very crucial for the safe operation of any structure. In the case of launch vehicle/ launch pad structures, the jet loads and acoustic loads experienced during the launch vehicle lift-off are random in nature. Fatigue life estimation under random loads are complex compared to harmonic loads. Several research works have been done in the area of health monitoring and fatigue life estimation under sinusoidal and random loading. In this work, an effort is made to understand the effect of fatigue damage on the dynamic characteristics of a simple beam structure under harmonic vibration loading and the prediction of residual life of a structure based on the change in the dynamic characteristics is proposed. Cantilever beam specimens of two different materials are considered in this study and the same were made to fail under harmonic loading for the predetermined number of cycles using an electro-dynamic shaker vibration testing setup. In this process, the variation of dynamic parameters of the test beams with the number of cycles of loading was monitored and the data is presented. Also, the initiation and propagation of crack was monitored till the damage of the beam. Hence, from the variation of natural frequency data, the residual life of the structure under study is predicted.

Keywords: *Fatigue life, natural frequency, electrodynamic shaker, strain gauge, accelerometer*

1. Introduction

Fatigue is a gradual process of local strength reduction. It is a phenomenon of damage accumulation at stress concentrations caused by fluctuating stresses and/or strains. In metals, this results in microscopic cracks. These will start to grow under continued cyclic loading until final failure occurs. The process of fatigue is essentially a process of crack growth. In general, the damage accumulation, i.e. crack growth, is slow in the early stages and at the end of fatigue life it accelerates very quickly towards failure. All engineering metals are sensitive to fatigue.

Fracture mechanics has become a perfect tool to deliver a useful methodology to compensate the inadequacies of conventional design concepts. The conventional design criteria are based on tensile strength, yield strength and buckling stress. These criteria are useful for several engineering applications, but they are insufficient when there is a crack in a structure. Hence integrity of many engineering structures is in jeopardy by the presence of these initial cracks. Even though the design may appear to be safe, but structure may fail due to aggravation of secondary cracks under same or low cyclic loads. These secondary cracks may grow either from the free surface or from the initial geometrical features such as notches. Hence it is essential to address the problem of notch under fatigue loads and

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consequent failure of the structures. Also, during the process of fatigue failure or crack growth under repeated or random loads, the dynamic properties of the structure tend to change. Monitoring the dynamic characteristics variation will be helpful in predicting the unexpected failures. In this study, the change of dynamic characteristics of a simple cantilever beam structure under harmonic vibration loading is evaluated. Also, it is proposed to predict the fatigue life of a structure from the change in dynamic characteristics.

2. Literature Review

The effect of fatigue life on the dynamic characteristics has been studied by various researchers. **Behzad Ahmed Zai et al [4]** proposed a methodology to predict the crack growth and fatigue life of a cantilever beam made of Acrylonitrile Butadiene Styrene (ABS) manufactured with fused deposition modelling. Three beam configurations based on length were considered and empirical relationships are formulated between the natural frequency and the crack growth. Using the experimental data, a global relation is formulated for the in-situ crack depth prediction with an error of less than 10%.

Mahantesh. Matur et al [5] studied the fatigue crack growth behaviour of an arc shaped specimen with inner surface notch. Stress intensity factor (SIF) values obtained by the numerical simulation for the single edge notch bend specimen showed a good agreement with the results obtained by photo elastic technique and hence using the same numerical simulation based finite element analysis (FEA) technique, an influence of presence of notch on the fatigue life of aluminium specimen was investigated by the numerical simulation and compared with experimental results. **Da Yu et al [8]** developed an assessment methodology based on vibration tests and finite element analysis to predict the fatigue life of designed PCB with ball grid array (BGA) package under random vibration loading.

Ed Habtou et al [9] developed a new method where the damage accumulation rate is computed in the frequency domain using Linear Elastic Fracture Mechanics (LEFM), stress intensity & the natural frequency and a finite element model was developed to predict the stress intensity and natural frequency during damage accumulation.

K Klein et al [12] investigated fatigue crack detection using modal analysis. Steel cantilever beams were subjected to repetitive cyclic stress. Periodic measurements with accelerometers, force transducers and pressure microphones recorded both the frequency response and pressure transfer functions of the specimens. The objective was to observe the changes in both vibration and acoustic variables that occurred with the presence of a fatigue crack. Shifts in natural frequency, damping and other parameters were documented as sample specimens were fatigued into cracking. From the mode shapes, it was observed that the crack's position was close to maxima of the fourth and fifth modes in both tests. The natural frequencies of the fourth and fifth modes were observed to be most affected. Likewise, the apparent damping coefficient increased for these modes.

3. Problem Definition

The main objective of the present work it to study the variation of natural frequency with the number of cycles of loading, when a structure is subjected to fatigue loading. The fatigue loading may be harmonic or random. This work deals with harmonic sinusoidal loads. The objective is achieved by designing a cantilever beam specimen with two different materials and subjecting it to the required strain and stress in order to make it fail at the predefined number of cycles of harmonic fatigue loading with stress ratio R = -1. The natural frequency variation is monitored during the fatigue loading at regular intervals till the failure of the beam. From the variation in natural frequency, it is proposed to predict the residual fatigue life of the structure.

4. EXPERIMENTAL SETUP0

4.1. PREPARATION OF BEAM SPECIMENS

In this study, beams with two different materials namely mild steel IS 2062 Grade B E250 and aluminum Al 6061 T6 are considered. The dimensions are selected appropriately for both the beams so as to achieve the required stress levels in the beam during vibration loading using electro-dynamic shaker. The edges and surfaces are prepared properly to avoid discontinuities, which may become the crack initiation point during fatigue loading. The dimensions of the aluminium and MS beams selected are 250*25*3 mm and 250*25*2 mm respectively and the beams are provided with a hole at one end for mounting the beam on the miniature electrodynamic shaker. Figure 1 shows the mild steel and aluminium beam specimens bonded with strain gauges. The strain gauges are bonded on to the beams very close to the mounting point as seen in Figure 1, where maximum stress is expected. In order to subject the beam to required stress and strains levels, so as to make it fail under fatigue for the calculated number of cycles, it is required to increase the mass at the free end of the cantilever beam. This was achieved by fixing predetermined mass blocks at the free end of the beam.

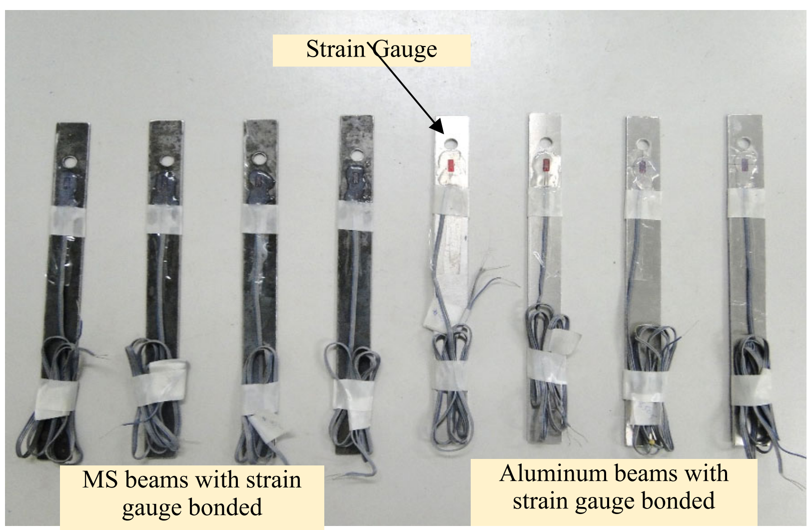

Figure 1: Mild steel & Aluminum cantilever beam specimens

4.2. TEST SETUP FOR VIBRATION LOADING AND EVALUATION OF NATURAL FREQUENCY

The experimental setup consists of a miniature electrodynamic shaker (MS 1000, Sentek dynamics), Power amplifier (Sentek Dynamics, LA 1500), tear drop accelerometers accelerometers (PCB make, Sensitivity range ~ 10mv/g, Model No 352C22), Strain gauges (FLAB-6-350-11), Strain gauge data acquisition card (National Instruments NI 9236 module), Chassis for data acquisition card (National Instruments NI cDAQ-9184), Computer with National instruments signal express software, Data acquisition system for vibration system (16 channel vibrunner AI810), Computer with m+p international software, Cantilever beam specimens, mounting fasteners, necessary tools and cables. The test setup is shown in figure 2. The cantilever beam specimen is mounted directly on the shaker table using suitable fasteners. A dummy mass of calculated weight is fixed on beam at the free end in order to achieve the required strain levels near the fixed end of the beam. One accelerometer is mounted on the fixed end while the other is mounted on the free end of the beam. The miniature electro-dynamic shaker is controlled by the m+p international vibrunner software through the data acquisition system and power amplifier. The same system is used to measure the vibration/acceleration levels on the beam through the accelerometers. The strain gauge data acquisition system consists of the strain gauge, NI 9236 strain gauge measurement module, NI cDAQ-9184 chassis and control computer using NI signal express software. The strain gauge is connected in quarter bridge configuration using the strain gauge measurement module. The estimation of natural frequency of the beam is carried out using the accelerometers and data acquisition system.

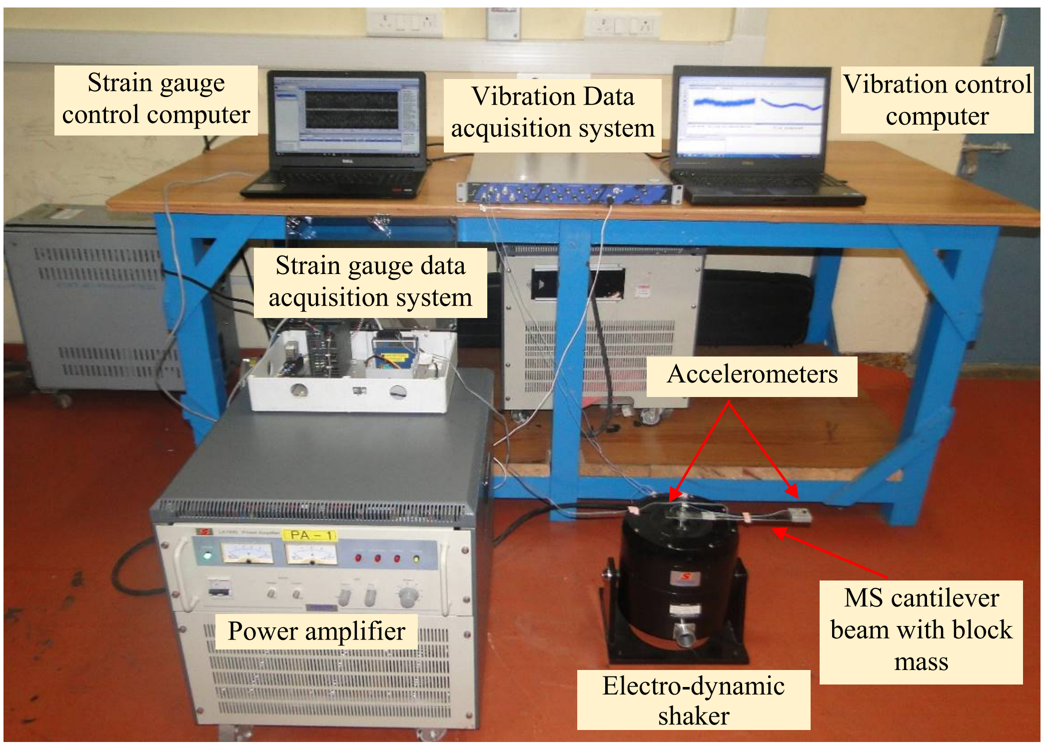

Figure 2: Experimental test setup for fatigue testing

5. Testing Methodolgy

In this study, the cantilever beam specimens are subjected to bending fatigue loading for the predetermined number of cycles to failure calculated using SN curve equations of mild steel [12] & Al 6061[13] and the variation in natural frequency of the beams till failure were recorded at specified intervals.

Initially, the test setup was arranged as shown in figure 2. The cantilever beam specimens bonded with strain gauge was mounted on the shaker table and the accelerometers are mounted on the beam specimen. Alignment of the beam is ensured and suitable torque was provided to the mounting bolts. After configuring the strain gauge data acquisition system and vibration data acquisition system, a tap test was performed to determine the natural frequency of the untested beam. Figure 3 shows the frequency domain data and time domain data measured during a tap test.

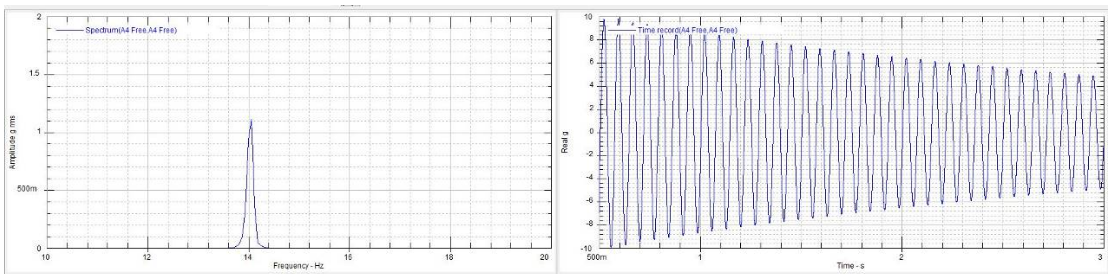

Figure 3: Tap test measurement – frequency and time domain data

From the predetermined no of cycles to failure for the selected beam specimen material, the corresponding stress was calculated using the SN curve relations available in literature. The equivalent strain for the stress calculated from SN curve relation was evaluated. After determining the natural frequency and strain, a sine dwell test is carried out for a small portion of the predetermined cycles using the miniature electro-dynamic shaker system at a frequency which is lesser and very close to the natural frequency so as to use the effect of resonance in achieving the required strain and stress at the fixed end of the cantilever beam. During the sine dwell test, the vibration levels are increased by quickly adjusting the gain in the amplifier till the calculated strain level is achieved at the strain gauge bonded near the fixed end of the beam specimen. At this strain level, the sine dwell test is carried out for the time duration corresponding to the small portion of predetermined of cycles of operation and the frequency. After the sine dwell test, tap test is carried out to determine the change in natural frequency of the beam specimen. The sine dwell test for the next few cycles of vibration loading is carried out again followed by the tap test to determine the change in natural frequency. The process is repeated until the beam specimen cracks and fails.

In this work, mild steel and aluminum beam specimens were tested considering the predetermined cycles to failure as 1,25,000 and 10,000 cycles respectively. From the SN curve relations, the equivalent strain to be subjected near the fixed end of the mild steel and aluminum cantilever beam specimens were estimated as $1.27 * 10^{-3}$ and $3.5 * 10^{-3}$ respectively. The natural frequency of the mild steel and aluminium beam specimens were close to 16 Hz and 14 Hz respectively. Four beam specimens of mild steel and aluminium were tested to check the repeatability of data.

6. Results and Discussion

The mild steel and aluminium beam specimens were fatigue tested using the miniature electro-dynamic shaker system to the predetermined cycles and the change in natural frequency were recorded. Figure 4 shows the variation of natural frequency of MS cantilever beam specimen against the number of cycles. As per the plan of the MS cantilever beam specimen fatigue testing, design cycles to failure was 1,25,000 cycles for a strain value of $1.27*10^{-3}$ strains. But the actual cycles to failure was found to be around 1,80,000 cycles. A crack was observed around 1,45,000 cycles which was accompanied by a small dip in natural frequency from 16.1Hz to 15.94Hz. From then, the crack propagation was observed and further dip in natural frequency was observed. The crack propagated and grew larger throughout the width of the beam, at the end of 1,80,000 cycles and the corresponding value of natural frequency was found to be 13.25Hz.

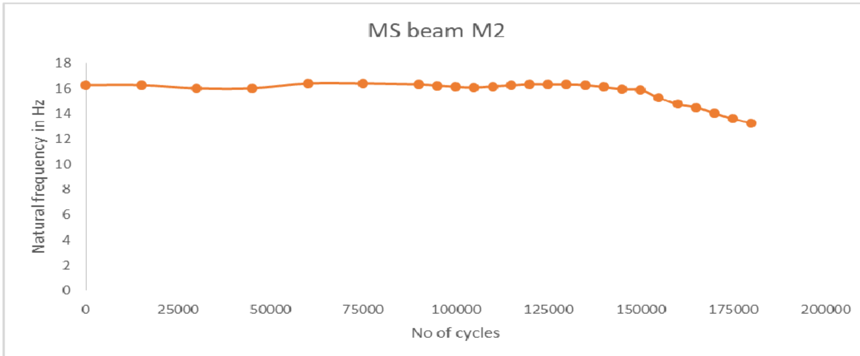

Figure 4: Natural Frequency Variation for MS Specimen

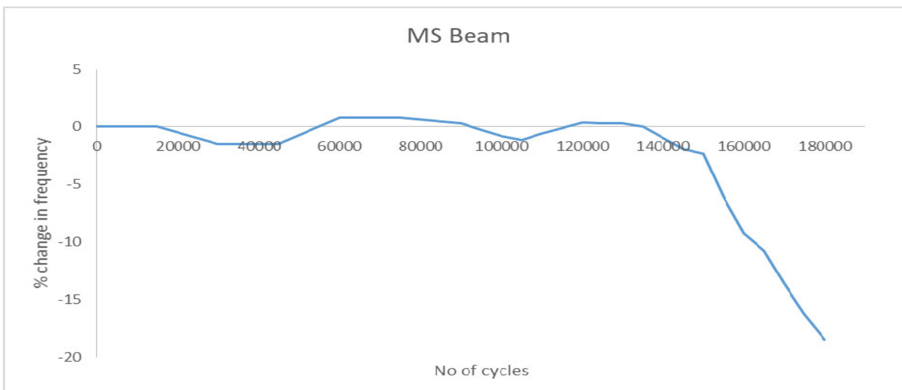

Figure 5: %Change in Frequency vs Number of Cycles for MS Beam

Figure 5 shows the % change in frequency with respect to the number of cycles. From figure 5, it can be seen that, after the natural frequency has reduced by nearly 5%, the residual life to failure is only 25000 cycles which is 13.8% of the actual life of 180000 cycles. Figure 6 shows the crack on top and bottom side of one mild steel specimen.

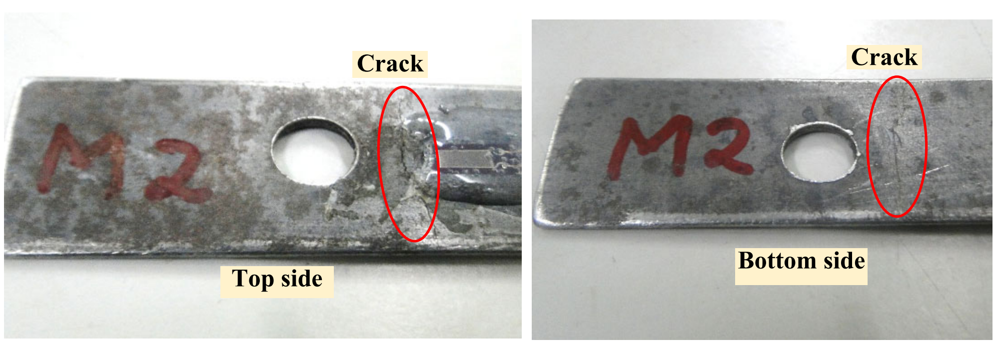

Figure 6: Crack on the top side and bottom side of MS beam

Figure 7 shows the variation of natural frequency of Al cantilever beam specimen against the number of cycles and Figure 8 shows the % change in frequency with respect to the number of cycles. As per the plan of the Al cantilever beam specimen fatigue testing, design cycles to failure was 10,000 cycles for a strain value of $3.5*10^{-3}$ strains. But the actual cycles to failure was found to be 10093 cycles with a deviation of 1%. A crack was observed around 9250 cycles that was accompanied by a small dip in natural frequency from 14.06 to 13.82. From then, the crack propagation was observed and further dip in natural frequency was seen. Figure 8 shows that, after the natural frequency has reduced by nearly 5%, the residual life to failure is only 468 cycles which is 4.6% of the actual life of 10093 cycles. The cracks observed on the surfaces of aluminium beam is shown in Figure 9.

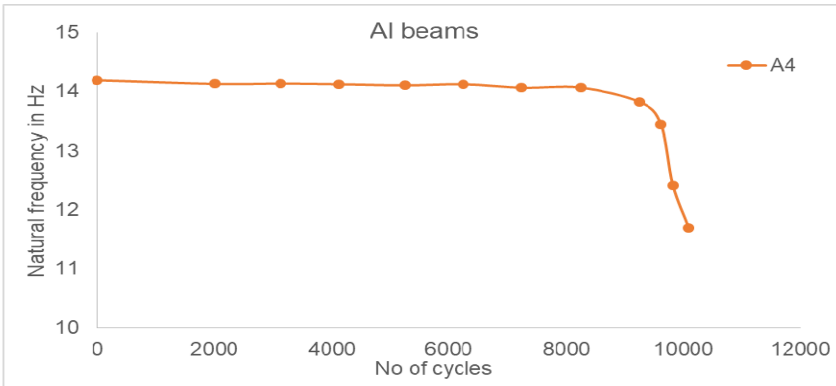

Figure 7: Natural Frequency Variation for Aluminium Specimen

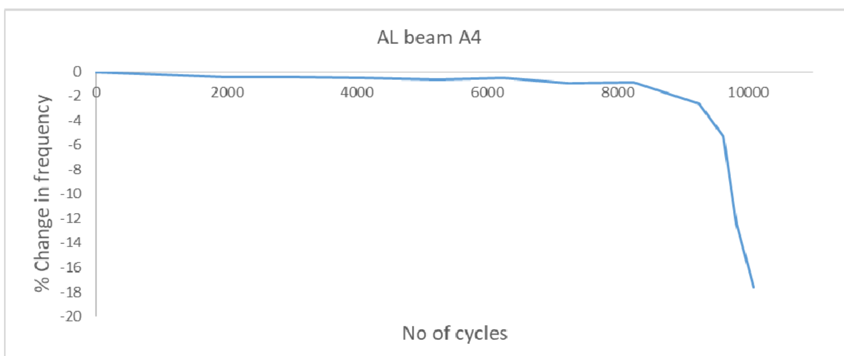

Figure 8: %Change in Frequency vs Number of Cycles for Al Beam

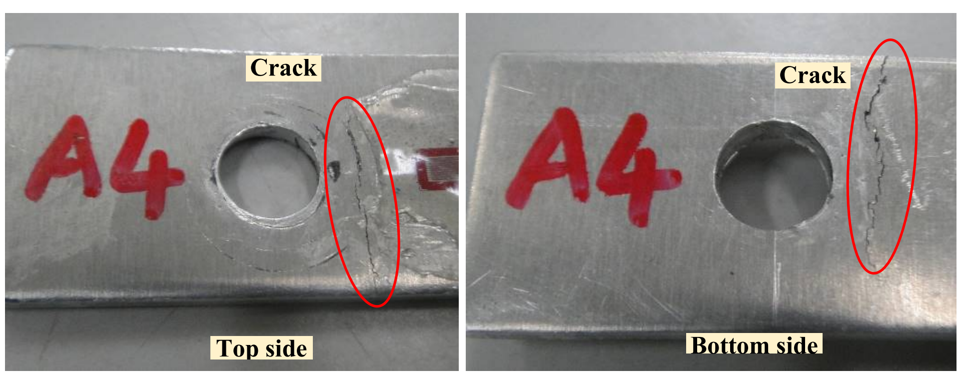

Figure 9: Crack on the top side and bottom side of Aluminium beam

The summary of the results of MS and Al beams are provided in Table 1. From the table, it can be seen that, after a reduction in natural frequency of 5% in mild steel and aluminium beam specimens, the residual life available was found to be 25000 and 468 cycles respectively. Hence for the cantilever beams of the selected size and material with harmonic loading, the residual life can be predicted from the change in natural frequency data evaluated in this work. The change in natural frequency and residual life with the change in size and shape and type of loading has to be studied. Also the change in residual life with random loading will be studied as an extension of this work.

Table 1: Summary of MS & Al beam test results

Description	**Design life in no of cycles**	**Actual life in no of cycles**	**% variation in no of cycles**	**Residual life in cycles after reduction in natural frequency of 5%**	**Residual life in % after reduction in natural frequency of 5%**
MS IS 2062 Grade B cantilever beam	1,25,000	1,80,000	30%	25000	13.8%
Al 6061 T6 cantilever beam	10,000	10,093	1%	468	4.6%

7. Conclusion

The variation of natural frequency of cantilever beam specimens made of IS 2062 E250 Grade B (mild steel) and Al 6061 T6 materials with respect to the number of cycles of fatigue loading was measured. The MS beam specimen was tested for a designed fatigue life of 1,25,000 cycles while the actual cycles to failure was found to be 1,80,000 cycles which is a deviation in life of 30%. Similarly, the Al beam was tested for a designed fatigue life of 10,000 cycles while the actual cycles to failure was found to be 10093 cycles. The deviation between the design life and actual life for the MS and Al beam specimen was 30 % and 1% respectively. The deviation of actual life with respect to design life is within the deviation levels for both the materials as specified in literatures. For MS beam, after the natural frequency has reduced by nearly 5%, the residual life to failure is only 25000 cycles which is 13.8% of the actual life of 180000 cycles. For Al beam, after the natural frequency has reduced by nearly 5%, the residual life to failure is only 468 cycles which is 4.6% of the actual life of 10093 cycles. Hence, this methodology can be applied to the health monitoring of critical structures for averting unexpected failures by monitoring the variation in natural frequency during its operation and determining its residual life.

8. Future Scope

The present work deals only with the study of variation of natural frequency under harmonic loading of plain cantilever beams with stress ratio of R = - 1. The same can be extended to beams with different stress ratios and in the presence of holes, notches, other discontinuities, etc. In this study, dimension of the beam is fixed and experiments are carried out. The present study can be carried out using beams of different sizes and different materials.

This study can be implemented to complex structures and methodology of continuous health monitoring of critical structures can be devised to avoid unexpected failures. Harmonic load conditions are comparatively simple compared to random loads. Majority of the structures are subjected to random loads. Hence the effect of fatigue and fracture under random loads and the associated variation in the dynamic parameters can be studied. Random loads are complex in a way that, it requires techniques like rain flow counting for determining the number of cycles of loading and its amplitude and the same can be explored. The natural frequency variation in the presence of a crack and the residual life after 5% reduction of the same is calculated for a cantilever beam specimen. A methodology can be developed to correlate the cantilever beam results to any structure and predict the residual life of the same.

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