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Finite Element Dynamic Analysis of Composite Structure Cracks

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***Abstract*—**Material damages dynamic analysis is difficult to deal with different material geometry and mechanism. In addition, it is difficult to measure the dynamic behavior of cracks, debond and delamination inside the material. Different simulation methods are developed in recent years for different physical features of mechanical systems like vibration and acoustic. Nonlinear fractures are analyzed and identified for different locations in this paper. The main idea of this work is to perform dynamic analysis on different types of materials (from normal homogeneous material to complex composite laminates). Technical factors like cracks, voids, interfaces and the damages' locations are evaluated. In this project the modal analysis is performed on different types of materials. The results could be helpful in finding modal frequencies, natural frequencies, Time domain and fast Fourier transform (FFT) in industrial applications.

***Keywords*—**Finite element method, dynamic analysis, vibration and acoustic, composite, crack, delamination.

I. Introduction

CRACK nucleation and micro crack formation may be caused by transient load swings. It may be higher than expected periodic loads or defective component materials in different components. Periodic loads cause fatigue and accelerate the cracks in materials like composites, plastics, ceramics, fabrics and metal alloys. Cracks occur in many different types of material and geometries. It causes damages in different type of mechanism or different parts of equipment. These problems are recently analyzed by some new techniques.

Crack size depends on material toughness. Stress levels are determined. Material damages lead to non-linear behavior. In addition, some material related factors like viscoelasticity can significantly change by structure stiffness during analysis. Moreover, material cracks and damages are analyzed with assist of forces decomposition technique. There are three types of failure modes. Firstly, the forces are perpendicular to the crack. In this situation the crack is horizontal and the forces are vertical. Secondly, the forces are parallel to the crack. Finally, the forces are perpendicular to the crack. In this case the crack is in front-back direction and the forces are pulling left and right [1].

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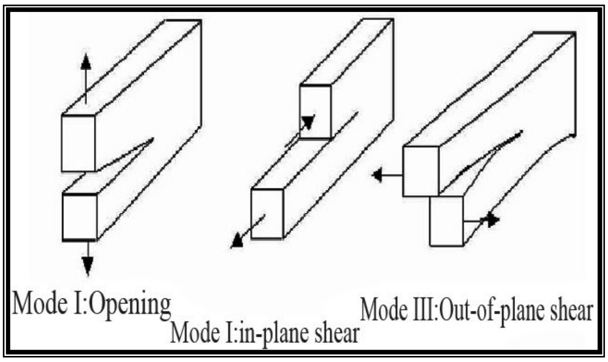

Fig. 1 Three types of modes in crack

Delamination is identified between the material molecules. Material work pieces are vulnerable and ready to breakage. Low strength materials are defected. Mould defects control during manufacturing increase products quality and strength. One of the most common observed failure modes in composite materials is delamination. Layers are stacked together to form laminates in composite materials. Delamination identified as fiber reinforced layers separation. The most common sources of delamination are in material and structural separation. Different types of delamination shown in Fig. 2. Delamination occurs at stress free edges mismatch in individual layers. Regions are subjected to out of plane loadings such as curved beams bending. These loadings are laminated the structure material, when thickness is reduced under applied pressure.

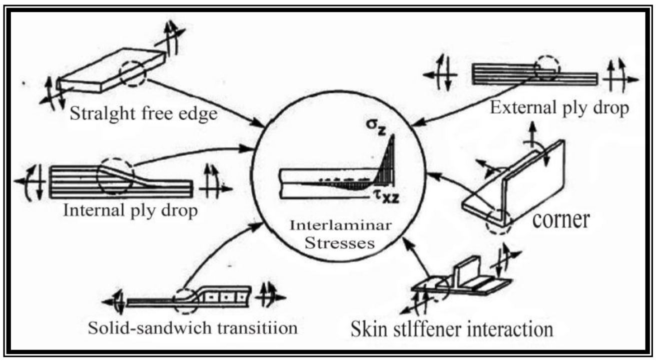

Fig. 2 Different types of delamination

In finite element method (FEM) the solid, liquid or gas materials are divided to finite number of specific parts. These parts are interconnected at specified joints called nodes. Nodes are lied on the element boundaries. ANSYS is a general purpose finite element analysis (FEA) software package.

ANSYS provides a cost effective way to explore the products performance or processes in virtual environment. There are three ANSYS Element types (PLANE82, PLANE182 and INTER202). Element type PLANE82 is used in this paper [2].

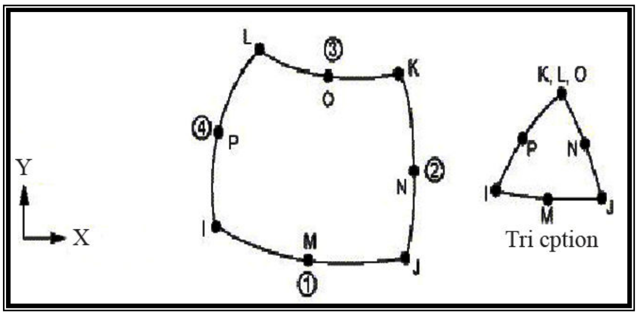

Fig. 3 Element type PLANE82

The damage intensity before the system failures is predicted by nonlinear dynamic analysis. This technique is performed in modeling of manufacturing systems. In addition, this method is used for time domain analysis in composite materials. Finite element method is applied in different aspects of mechanical engineering.

This study aims to investigate the expansion characteristics. The proposed model is close to real conditions. Nonlinear model contains balloon, stent and vessel with plaque. Bi-linear elastic-plastic model for stent, hyper elastic balloon, artery and plaque have been assumed [3].

M-R form constitutive equation is included in several finite element codes. This method is readily applicable to stent design. The results of finite element method include stress distribution, radial gain, outer diameter changes and dog boning [4].

Finite element method is performed in civil engineering, agricultural science and metallurgical studies. Finite element method (FEM) was used to predict soil sink by multiple loadings of a rectangular plate. Besides, two-dimensional FEM program entitled PRESSINK was modified and employed to perform required numerical calculations [5].

Finite element is the best method that can be used to visualize stress distribution and displacement. Several different soft wares are developed base on this method in recent years [6]. Finite element model based on the experimental observations of dominate fatigue kinked crack angle and the crack path was used for simulating the fatigue crack in the spot welded joints. Furthermore, the linear elastic fracture mechanics was used to obtain the local stress intensity factors related to fracture modes [7].

Dynamic analysis sometimes is performed by homotopy Perturbation Method. This method is applied in different applications like symmetric rotor with gyroscopic effect. In such cases, equations of motion have been derived from Lagrange equation. These equations are solved by analytical and numerical methods [8].

The application of dynamic analysis is not limited to engineering science. It has wide applications in critical geoscience. These methods are affected our everyday life. Nonlinear dynamic analysis of complex time wave forms like earthquakes are applied successfully in recent years [9].

In addition, simultaneous analysis of dynamic crack growth with faces contact (for two dimensional time domain) is developed too much in recent years. Displacement and traction boundary integral equations are used for one region in the same time. The proposed methods are evaluated automatic crack propagation modeling. Some new elements are added in front of crack tips in these techniques [10].

II. Literature Review and Significance of This Method

A. Background Researches

In homogenous material systems, damage almost involves cracks. The crack nucleation and micro crack formation are evaluated and identified by dynamics and fracture mechanics. Transient load swings and high intermittent loads are caused crack nucleation and micro crack formation. Configuration changes could cause by normal wear in dynamic loading mechanisms. These conditions are cause micro crack formation at grain boundaries. These cracks are appeared usually in stress concentrated regions.

Structural systems are composed of homogeneous or heterogeneous materials such as composites, plastics, ceramics, fabrics and metal-alloys. Heterogeneous structures have complicated dynamics of their modes (crack growth, delimitations, fiber breakage, matrix cracking and component failures). These modes are interacted in complicated ways. The paths are varied tremendously for different initial states, level of damage and loading history. In addition, time domain techniques can accommodate the diversity of failure modes exhibited by structures. It is worthy to know that, time domain called time wave form (TWF) in condition monitoring technical documents. Various types of composites and homogeneous materials TWF and FFT is plotted.

B. Fracture and Damage Mechanics

Crack and flaws occur in many structures and components. These cracks sometimes cause disastrous results. Fracture mechanics develop a basic understanding of crack propagation in different mechanism.

How a crack or flaw in a structure propagates under applied loads? This question is answered in fracture mechanics. It involves analytical predictions of crack propagation. These methods consist of experimental results. The analytical predictions are made by fracture parameters calculation. Fracture parameters such as stress intensity are used to estimate crack growth rate. The crack length is increased with cyclic load. Further environmental conditions like temperature or extensive exposure affect the fracture propensity.

C. Significance of This Method

The objection of fracture mechanics is to provide quantitative answers to specific problem. This method concerns cracks in structures. But, in real applications the cracks grow with time because of various causes like fatigue, stress, strain, corrosion and creep. Cracks generally grow progressively faster. The residual strength of the structure decreases with increasing in crack size. These factors are considered in this study. Residual strengths are decreased too much. This may cause structural collapse in certain areas. Both situations are represented in Figs. 4 and 5.

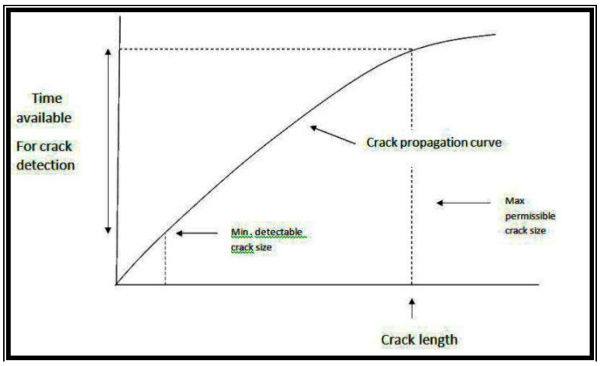

Fig. 4 Crack engineering problems (structure A)

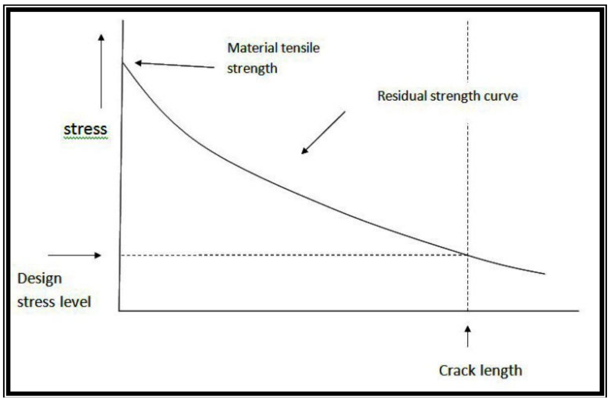

Fig. 5 Crack engineering problems (structure B)

D. Motivation of the Approach

Nonlinear dynamic analysis detects damaged materials. The damage intensity is predicted before failures. It is an important factor in manufacturing and modeling. Dynamic analysis is successfully performed for composites and homogeneous materials. Time domain technique in dynamic analysis is essential for damage detection in machines components and industrial structures. This work is regarded to some new aspects in damages prediction.

III. Main Parameter

A. Material Toughness

Material toughness is defined as ability to carry deform plastically load in the presence of notch. It can be described in terms of critical stress intensity. This factor is calculated under condition of plane stress with linear elastic behavior.

B. Crack Size

Brittle fracture start from extremely small cracks to very large weld or fatigue cracks. Small cracks can grow by fatigue or stress corrosion. Stress, strain, fatigue, creep and fracture are identified by conventional methods.

Temperature, loading rate, stress concentration and residual stresses could cause susceptibility of structures (brittle fracture). Condition monitoring (CM) is predicted fractures in industrial applications.

C. Stress Level

Tensile stresses are caused brittle fracture. These stresses are determined by conventional stress analysis. These techniques are applied for particular structure. Temperature, loading rate, stress concentration and residual stresses are considered as critical factors. These factors can predict the susceptobility of various structures.

IV. Damages in Heterogeneous Materials

Damages in material usually lead to nonlinear behavior like structural nonlinearities characteristics on a routine basis. For instance, the metal staples deformation. Overloaded wooden shelf will collapse. The contact surfaces between pneumatic tires and the underlying pavement change in response to the added load in automobiles. The fundamental characteristic and structural stiffness of nonlinear structural behavior is shown in Fig. 6.

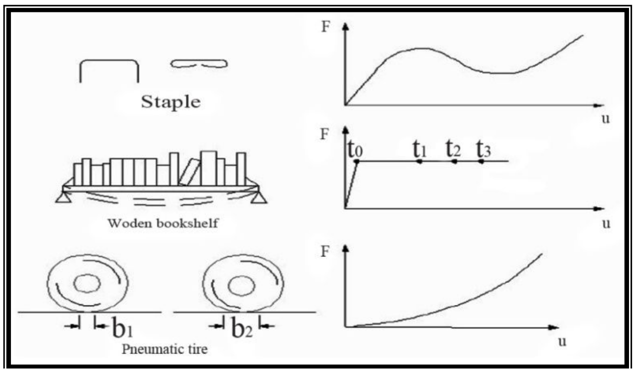

Fig. 6 Load deflection curves for different types of structural nonlinear behavior

Nonlinear structural behavior arises from a number of causes like material and geometric nonlinearities.

A. Geometric Nonlinearities

Changing in geometric configuration can cause nonlinear behavior in large deformations. In addition, geometric nonlinearity is characterized by "Large" displacements and rotations.

B. Material Nonlinearities

A number of material related factors can cause structure's stiffness changes. Nonlinear stress-strain relationships of plastic, multi linear elastic, and hyper elastic materials cause changes at different load levels and temperatures. Creep, fatigue, viscoplasticity and viscoelasticity are increased. Strain is a function of temperature, time, neutron flux level and stress.

Viscoplasticity occurs because of fracture near crack tips.

The cracks hold certain radius of curvature. Plasticity region highly depends on type of material. Besides, plane strain and stress are considered as important factors.

V. Experimental Details

Nonferrous metal with density of aluminum is a kind of homogeneous material with material properties like (ρ) = 2700 kg/m^3, Poisson's ratio of aluminum (v) = 0.3 and Young' modulus of aluminum (E) = 7*1010 pa. In addition, velocity of sound in Aluminum (v) is calculated form the following equation.

$$c_p = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}} = \sqrt{\frac{7*10^{10}(1-0.3)}{2700(1+0.3)(1-2*0.3)}} = 5907.64\ m/s$$

Aluminum is considered as a homogeneous material. Aluminum modeling systems are based on this fact. Minimum 20 elements per wavelength are required to analysis. Mentioned material properties are applied in ANSYS simulation system. The time variant dynamic force is applied at the top and Bottom. Reflection occurs at the interfaces because of the difference in aluminum and air impedances.

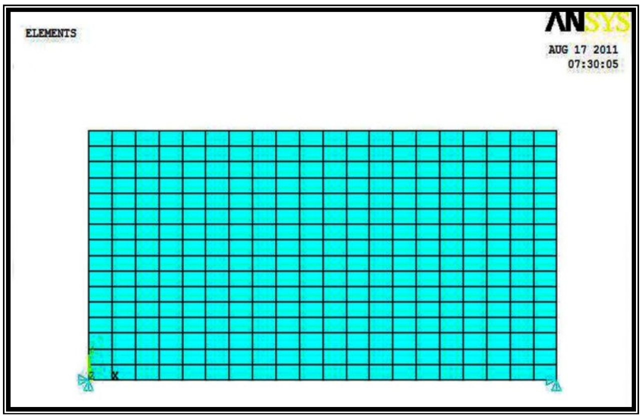

Fig. 7 Homogeneous material with elements solid model

First 5 natural frequencies are presented in Table I. The force 0.01N is applied on top at 0.5m from left edge (the center of the model).

TABLE I
Modal Frequencies

SET	TIME/FREQ
1	637.39
2	655.87
3	849.66
4	1897.5
5	2658.1

Frequency response analysis is determined steady state response of a linear structure. The loads are fluctuated and varied (harmonically with time). The structure's responses at several frequencies are calculated. Displacement versus frequency is obtained. These graphs called fast Fourier transform (FFT) in vibration analysis [11]. Peak responses are identified on the graph. Stresses are reviewed at those peak frequencies. The sustained structure is analyzed. Dynamic behavior is predicted by Harmonic response analysis. Resonance, fatigue, and other harmful effects of forced vibrations are predicted through these kinds of technical graphs [12]-[14].

0.01N is applied at the middle node on surface. Frequency analysis is performed for the same model. Frequency band is adjusted between 0 to 10 kHz and 0 to 100 kHz. Frequency resolution is taken as 100 Hz. Transient dynamic analyses are performed.

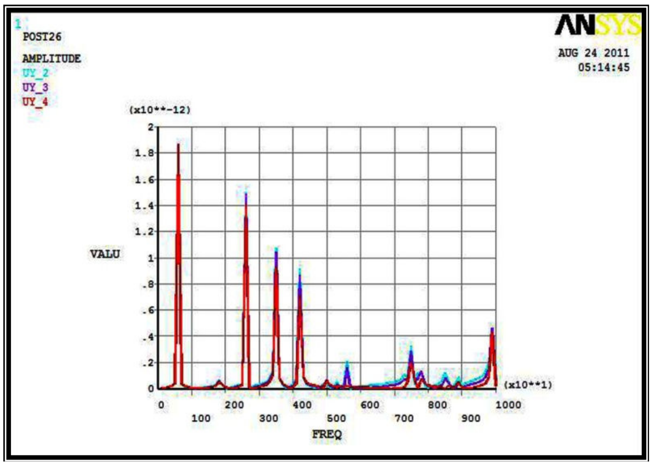

Fig. 8 Frequency response between 0 and 10 KHz

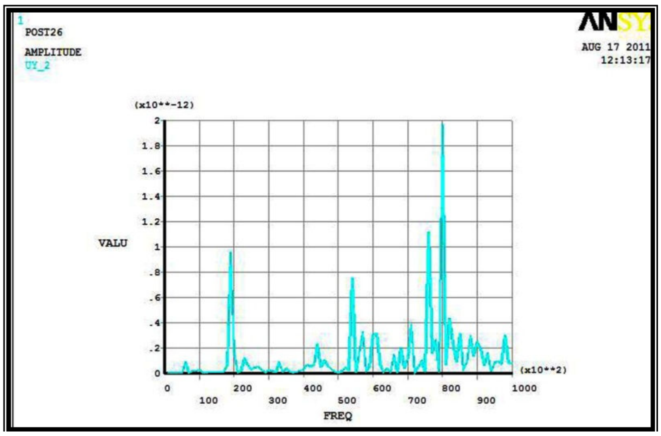

Fig. 9 Frequency response between 0 and 100 KHz

Transient dynamic analysis sometimes called time history analysis. This method determines the dynamic response of structures under time dependent loads. This analysis determines the variation of time via displacements, strains, stresses, and forces. These factors vary by static, transient, and harmonic loads.

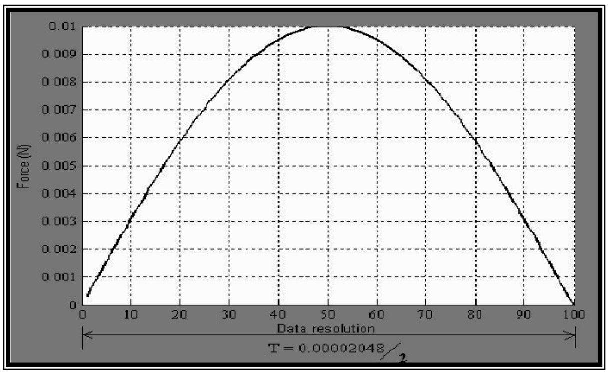

Fig. 10 Mechanical impact generates stress waves

The dynamic force is applied to top center and responses were plotted at three points.

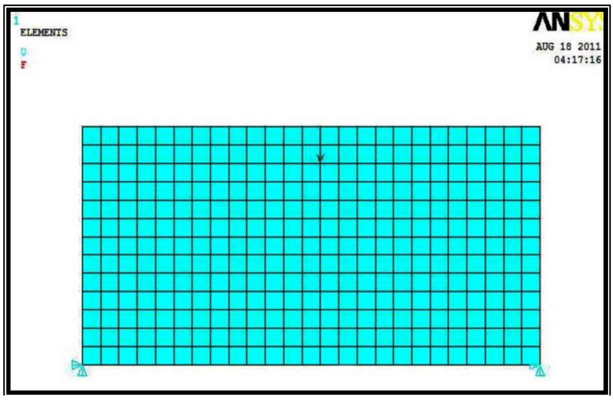

Fig. 11 Solid model constrained at bottom extreme nodes and showing impact point and response points

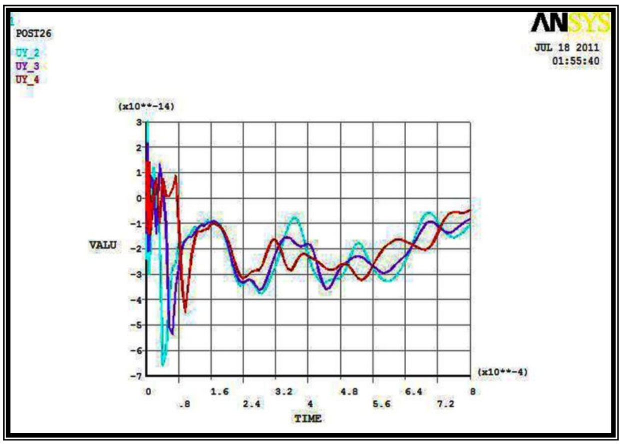

Fig. 12 Time domain responses at 3 points of the model which is constrained at the bottom extreme nodes

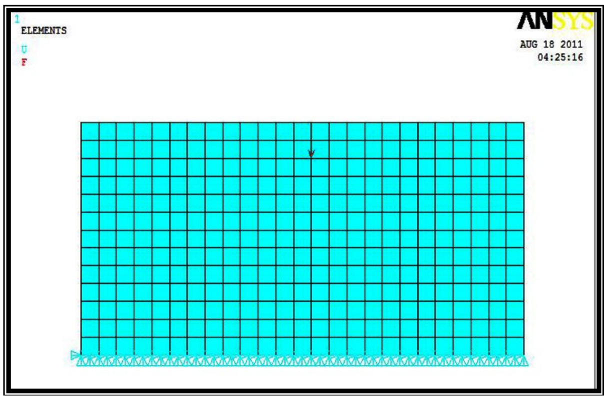

Fig. 13 Solid model showing impact point and response points where the bottom nodes are constrained

The entire bottom nodes are constrained when the dynamic force is applied at the center of model. The responses at l, 2 and 3 is plotted as time domain plot shown in Fig. 14. Besides, time domain called time wave form (TWF) in condition monitoring technical documents. Basic principal and application of time domain analysis discussed in [11], [13], [14].

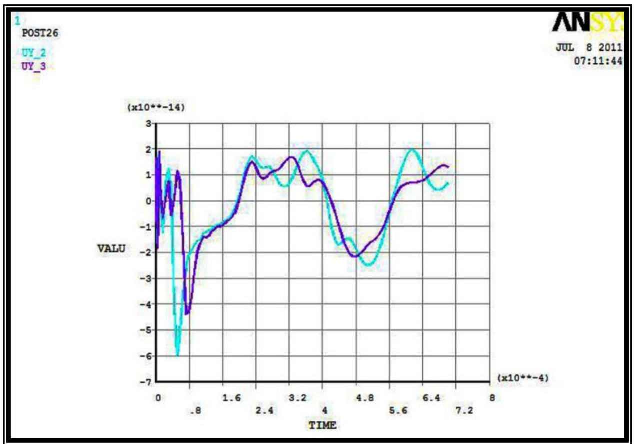

Fig. 14 Time domain responses at three points of the model which is constrained at all bottom nodes

Nodal displacement for finite element meshes plots are represented in Fig. 15. The Pressure wave is located at bottom of plate. This wave returns to the surface at the next stage. The Shear wave reflection is traveled to the surface. The locations of the various waves are seen clearly.

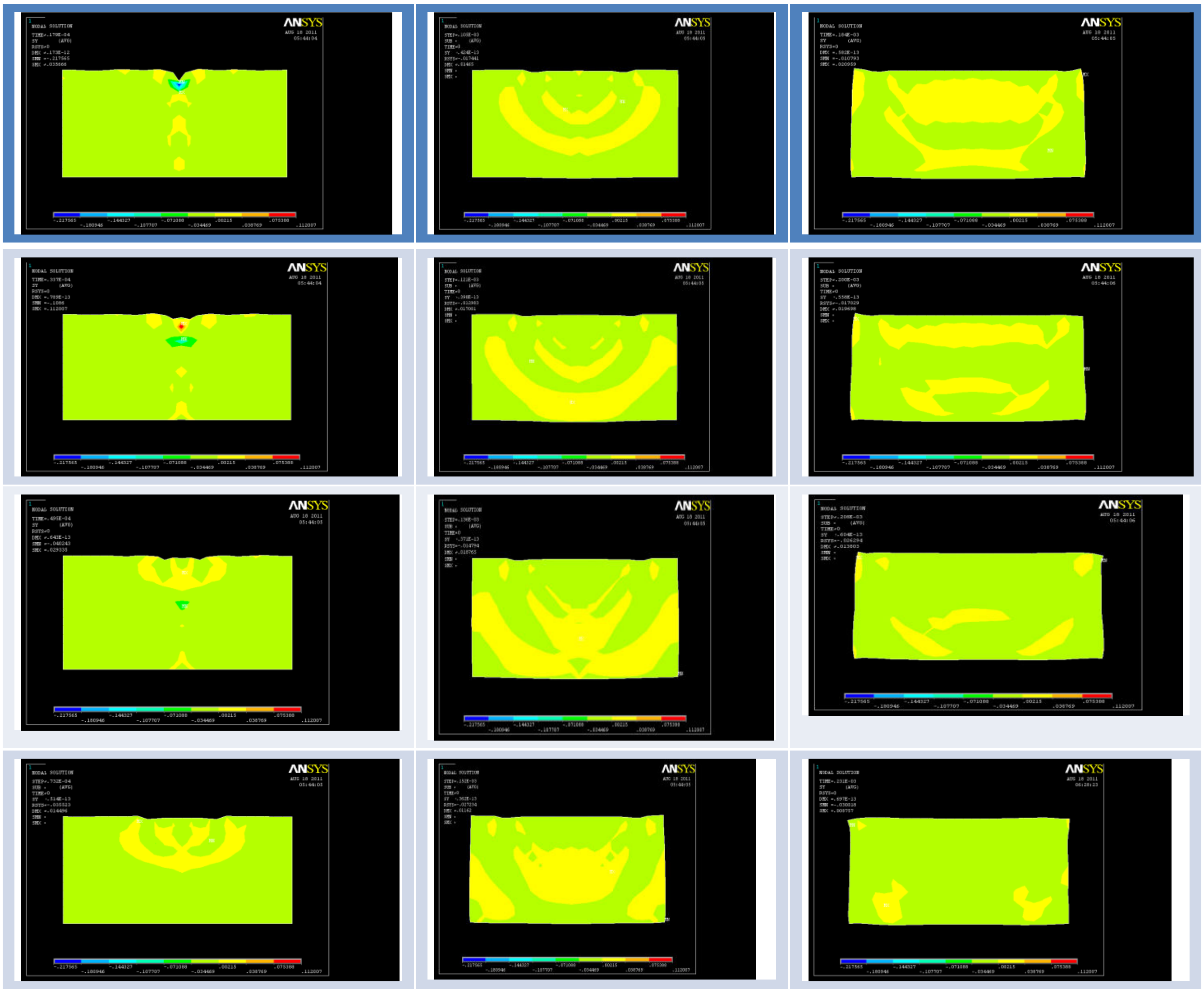

Fig. 15 Finite element simulation of impact on a plate, from top left to down, series of shear diagrams

Waves propagate through the material at different times. Pressure wave strikes the surface after reflection at bottom (right pictures). This analysis can be performed in many different ways. For example the sound speed can be evaluated when specimen width is identified.

VI. Homogeneous Material with Crack

Homogeneous material is assumed as aluminum alloy. Small crack is modeled at 0.25m form the top and 0.5m from the side edges. It is an elliptical shaped crack having dimensions 0.2mm major axis and 0.0001mm minor axis. Aluminum density (ρ) = 2700Kg/m^3, aluminum Poisson's ratio (u) = 0.3, aluminum young's modulus (E) = 7x10pa, velocity of sound in aluminum (v) = 5907.64 m/s. Modeling is performed by solid 82 type elements in ANSYS. Solid 82 type elements are suitable cases to predict singularity near the crack tip regions (elliptical shape mesh was generated near crack tips). The whole model is meshed coarsely to reduce the computer resources except at the crack tips. Bottom extreme nodes were fixed. Homogeneous material finite element model with a center crack is presented in Fig. 16.

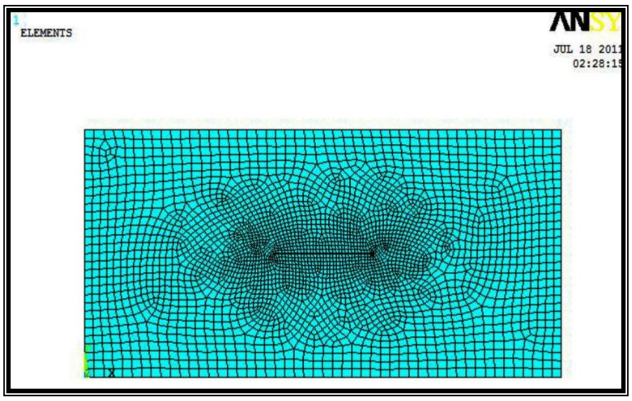

Fig. 16 Finite element model of crack within homogeneous material

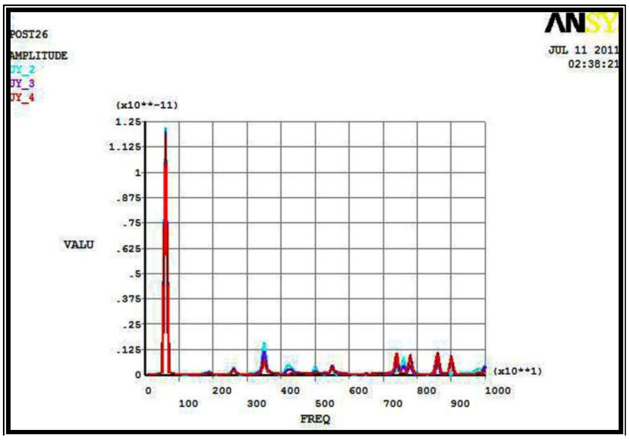

Fig. 17 Frequency response plot between 0 Hz to 10 kHz at various points

Vibration characteristics like natural frequencies and mode shapes are determined. These characteristics are calculated for static structures or machine component. Some successful and analytical case reports are discussed in [11]-[14]. Besides, these techniques are applied in machine design. ANSYS modal analysis is a linear analysis. Nonlinearities, Plasticity and contact (gap) elements usually ignored during modal analysis. Modal analysis is performed in first 5 modal frequencies. Modal frequencies are tabulated below (Table II).

TABLE II
MODAL FREQUENCIES

SET	TIME/FREQ
1	623.29
2	635.27
3	844.21
4	1880.2
5	2631.1

Frequency analysis is performed on ranges 0 to 10 kHz and 0 to 100 kHz. Initial force 0.01 N is identified. Frequency resolution is taken as 50 (The suggested frequency resolution was more than 1024 but this resolution is time consuming). The impact time is calculated (in similar way with homogeneous materials).

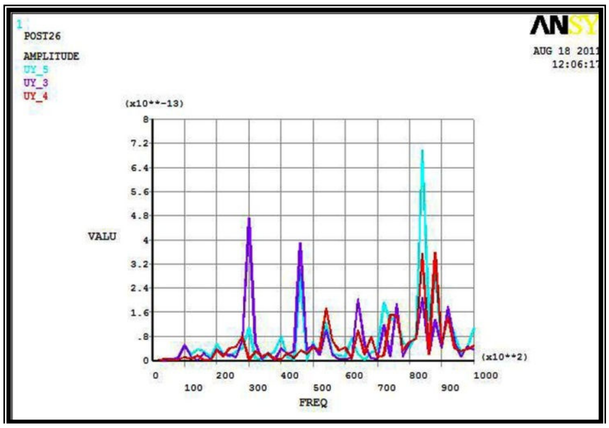

Fig. 18 Frequency response plot between 0 Hz to 100 kHz at various points

Dynamic analysis is performed on the cracked materials by applying the dynamic force. This force is applied at the middle of the surface. The same impact force as previous parts is applied. This force is applied with different impact time. The displacement-time and velocity-time plots are presented in Figs. 19 and 20. Besides, response points are fixed at the same distance from the impacted point.

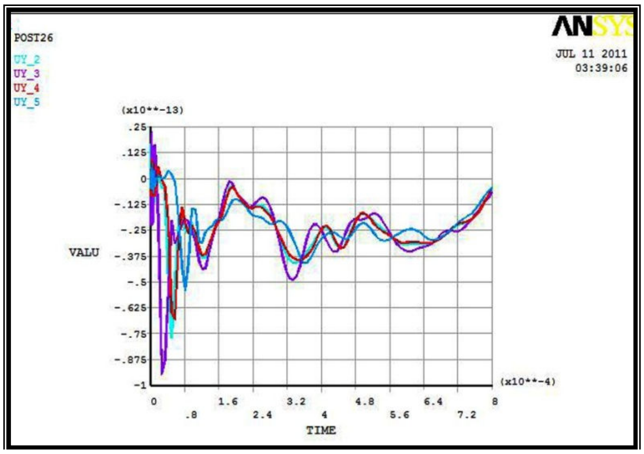

Fig. 19 Displacement-Time plots

The crack pressure wave is almost near the surface. The shear wave is just strike to the cracked surface. The speed of shear wave is about half of pressure wave.

Fig. 20 Finite element simulation of impact on a plate, from top left to down, series of diagrams of shear wave

This time the same analysis is performed with a crack in all directions. The bottom 2 nodes are fixed. The dynamic impulse force is applied at the surface center. The displacement amplitudes of three consecutive responses are recorded and plotted. The results are sorted from left of the impact point.

Crack frequency peak in FFT is called flexural vibration. The first natural frequency of flexural vibration depends on crack length and depht of crack. This flexural frequency is always less than the thickness frequency.

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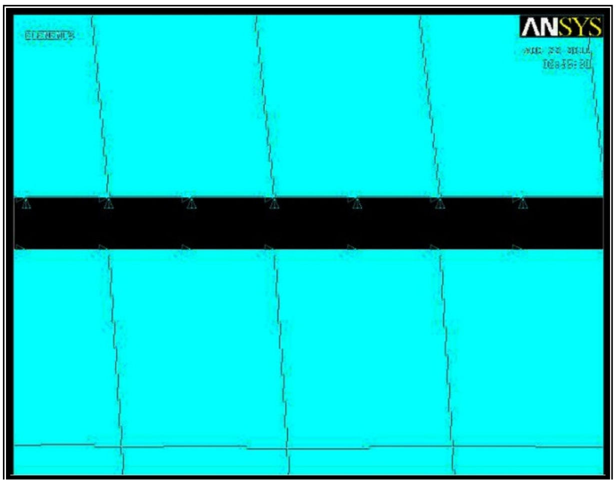

Fig. 21 Finite element model with crack fixed

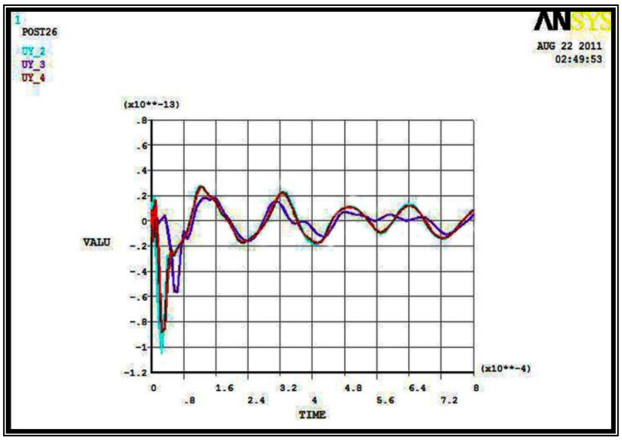

Fig. 22 Displacement – Time plots

Stress intensity factor near crack is shown in Fig. 23. In this figure a quarter of plate is shown because of model symmetry. The crack tip region is meshed using singular quarter point with eight node quadrilateral elements (PLANE82).

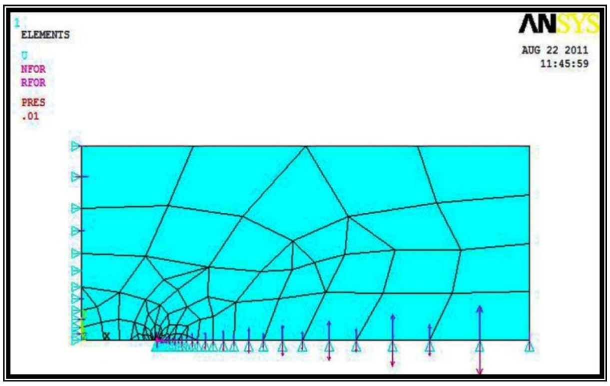

Fig. 23 Quarter model of cracked material

Stress Intensity factor (Kt) is found 0.05618. The flexural frequency is found 85.984 Hz. The thickness frequency is 10 kHz. Flexural frequency is less than thickness frequency. The stresses around the crack tip are increased too much. In addition, the crack tip region is transformed into nonlinear or plastic regions.

VII. Heterogeneous Material

Heterogeneous material is assumed as the combination of aluminum and low carbon steel. The alloy is AISI 1000 Series Steel with the following material properties. Density (ρ) = 7872Kg/m^3, Poisson's ratio (u) = 0.29, Young's modulus (E) = 2x10 11 Pa. Besides sound velocity (v) is available in handbooks and technical documents.

Material properties of aluminum are determined. Density (ρ) = 2700 Kg/m, Poisson's ratio (u) = 0.3, Young's modulus (E) = 7x1010 Pa, and sound velocity (v) = 5907.64 m/s.

Modeling is performed using plane 82 type elements. The upper material is a low carbon steel. The lower material is aluminium. The layers thickness is equal to 0.25m. Model is assumed as simply supported. All nodes are fixed in different directions.

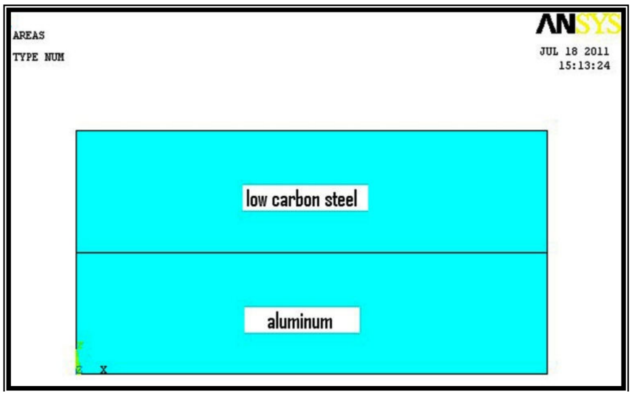

Fig. 24 Solid model of heterogeneous material

Mode I analysis is performed. Heterogeneous material frequencies are less than homogeneous materials.

TABLE III
Modal Frequencies

SET	TIME/FREQ
1	424.85
2	433.85
3	549.39
4	1656.5
5	2551.3

Frequency analysis is performed. Initial force is 0.01N at the middle. Frequency bands are identified as 0 to 10 kHz and 0 to 100 kHz. Frequency resolution is 25. The results are presented as displacement via frequency. Excitation frequency is calculated like previous sections.

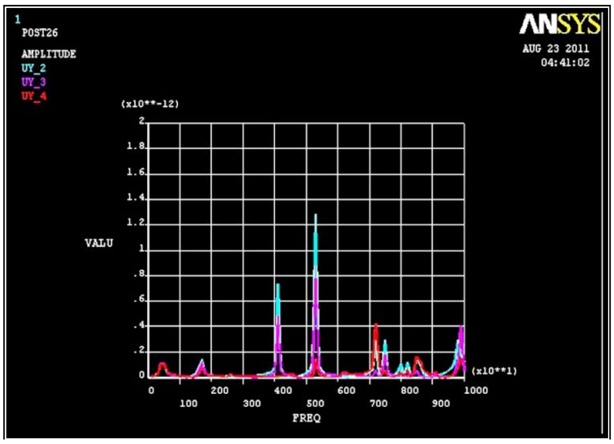

Fig. 25 Frequency-time plot with frequency range 0-10 kHz

Dynamic analysis is performed using the same excitation force. Different impact time at the middle is identified like previous sections. Three different points and three consecutive nodes are located at impact point left side. The results are presented as displacement via Time.

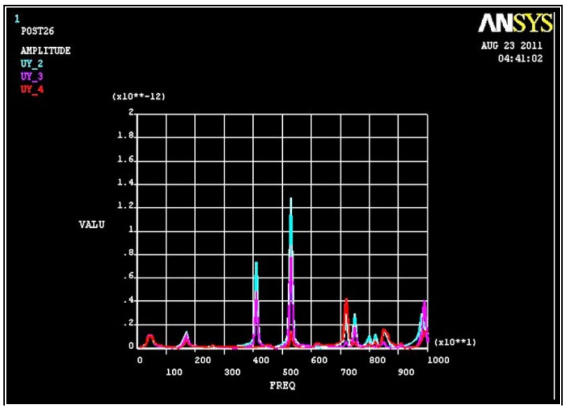

Fig. 26 Frequency –time plot with frequency range 0-100kHz

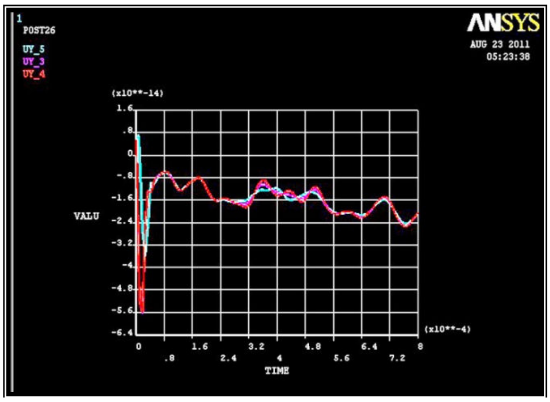

Fig. 27 Dynamic responses

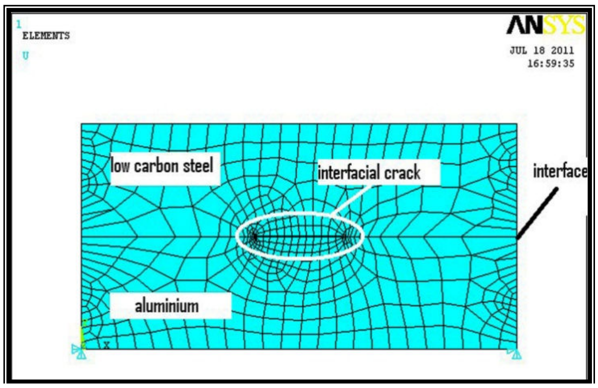

Fig. 28 Solid model of a heterogeneous material with an interfacial crack

VIII. Heterogeneous Material with Crack

Heterogeneous material is assumed as the combination of Aluminium and Low Carbon Steel. The crack is situated exactly at the interface between steel and aluminum. This situation is called interfacial crack. Material properties of aluminium and low carbon steel are indicated in previous section.

Initial force is 0.01 N. this force is applied at the node center. Modal analysis reveals natural frequencies. Natural frequencies are increased. First five natural frequencies are obtained.

TABLE IV
Modal Frequencies

SET	TIME/FREQ
1	592.03
2	601.17
3	794.98
4	1846.3
5	2598.7

Frequency analysis is performed. Initial force is 0.01N. This force is applied to surface middle node. Frequency ranges are 0 to 10 kHz and 0 to 100 kHz. Frequency resolution is 50. FFT graphs are plotted.

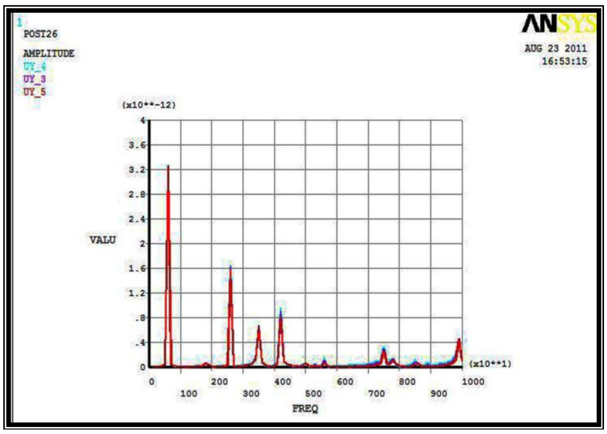

Fig. 29 Frequency response of various random points

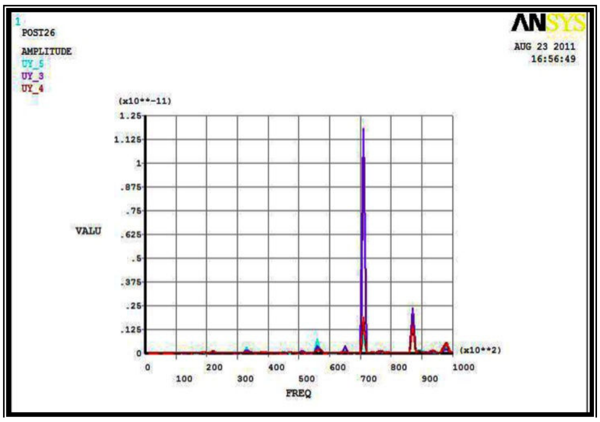

Fig. 30 Frequency response of various random points

Dynamic analysis is performed. Impact force is applied at the middle surface node like previous sections. Force intensity is 0.01 N. this force is enough to excite all structural modes. The crack is situated at the interface. Material densities are different. Therefore the crack reflection is stronger. The amplitudes are increased compared with the heterogeneous material. The mechanism is simply supported. Therefore, amplitudes are in the negative side.

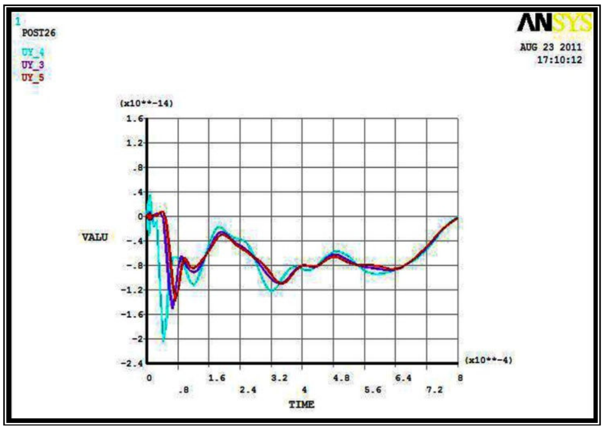

Fig. 31 Dynamic responses of three different points separated by equal distance front the impact point

A crack is embedded at the center of aluminum material. This crack is surrounded by two low carbon steel layers shown in Fig. 32. Cracks are occurred for different reasons. Differences in materials densities and coefficient of elongation may cause cracks.

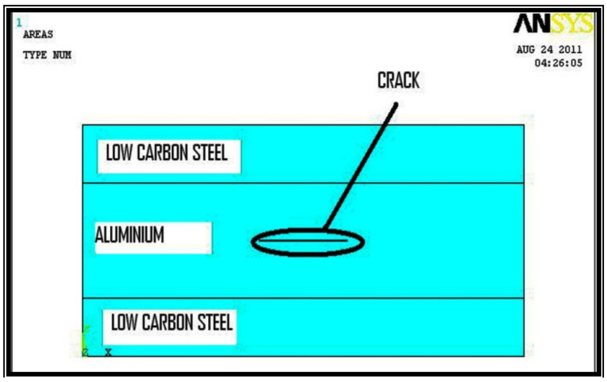

Fig. 32 Solid model of a crack embedded at the center material in composite laminate

Frequency analysis is performed. Frequency range is 0 to 100 kHz. Displacement via frequency is plotted. The number of FFT peaks is increased [15].

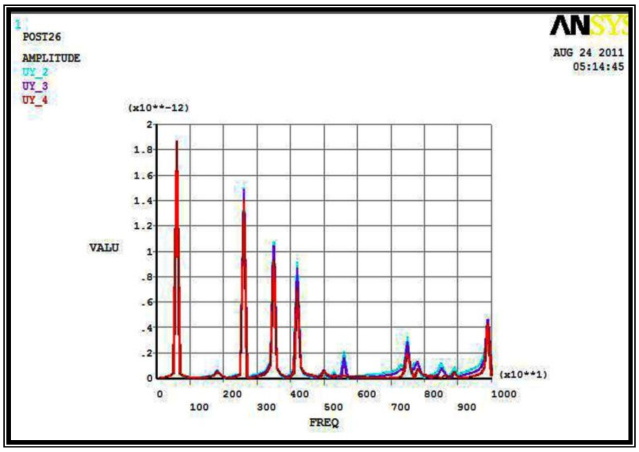

Fig. 33 Frequency responses

Several methods are developed in recent years in cracks vibration analysis. One of them is a domain decomposition Method. This method is developed for analyze the vibration of beams. Arbitrary number of cracks is considered. The analysis is performed through a recursive way employing some simple mathematical operations. The natural frequencies are closed form series (mode shapes solutions). These shapes can be obtained by solving a set of algebraic equations [16].

The shaft crack diagnosis is difficult. Shaft crack is hard to diagnose in most critical equipment. The crack may be longitudinal or radial. Cracks sometimes have microscopic diameters. Shaft cracks could be detected by amplitude and phase monitoring. In addition, second harmonics of RPM could identify small cracks. Besides, coast down and run up monitoring when rotor speed passing through resonance could identify the cracks [17]-[19].

New algorithm is developed by combination of fracture mechanics, photo elasticity's equations and digital image analysis to determine stress intensity factors. Errors are occurred when stress intensity factors are extracted from photo elastic fringe pattern. The estimated errors do not contain the errors associated with the optical apparatus. These errors consist of data discretization and extraction. Stress intensity factors are calculated. Series of fringe pattern were simulated. This simulation is performed in finite strips under remote tensile loading [20].

IX. Results and Discussion

Delamination of composites, ceramics and polymers are considered in manufacturing and design. Nowadays concretes are coated with fiber reinforcement polymers.

In addition, cracks in high shear strength areas, cause delamination or debonding (for fiber reinforcement polymer from structures). Concrete structure brittle failure could cause fiber reinforcement delamination. Delamination of fiber reinforcement polymers occur at the end anchor in the intermediate cracks [21].

The most common kinds of defects in composite structures are delamination, disbanding, and wrinkles. These defects are detected by shearography [22].

X. Delamination Analytical Data

Double cantilever beam with 100mm length, 20mm width and 3mm height is considered. Initial crack of 30mm length at the free end is considered. The crack is subjected to a maximum vertical displacement 10mm. vertical displacement is located on top and bottom free end nodes. Vertical reaction at point P is determined based on the interface vertical displacement.

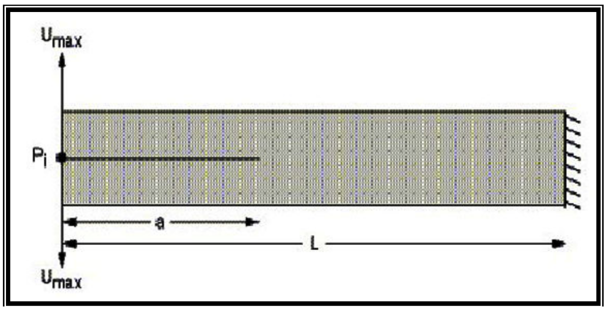

Fig. 34 Double cantilever beam with an initial crack

XI. Final Modeling

Two dimensional plane strain analysis is performed using regular mesh of 4 x 300 four node INTER202 elements. Imposed displacement of Uy = 10mm acts at the free nodes top and bottom.

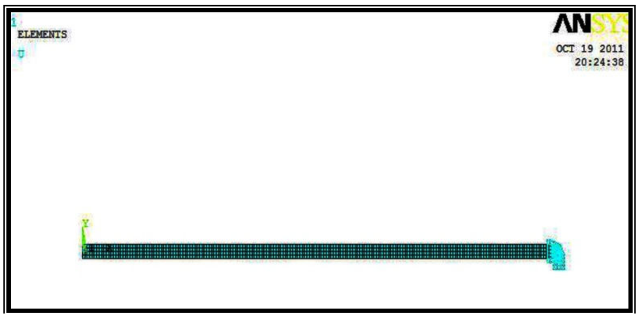

Fig. 35 FEA model of delamination

XII. Final Result

The displacement is applied. The maximum load before beam failure is detected (allowable load). This load is 60 N.

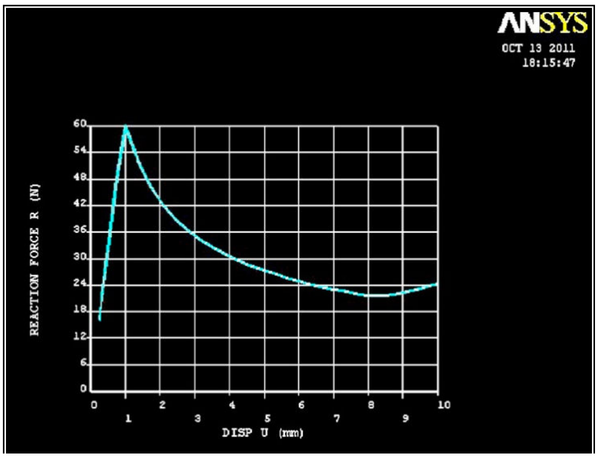

Fig. 36 Reaction force and displacement

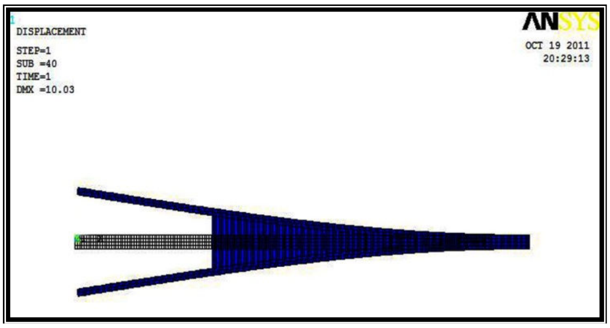

Fig. 37 Delamination deformed and unreformed shape under 10 mm of displacement

XIII. Current and Future Development

Dynamic analysis is an effective method in composite materials. Material properties, shapes and diversity could be successfully evaluated in this method. The excitation force is dynamically fluctuated on the structure in industrial cases and excitation point is hard to detect in computer software.

Material damages are predicted without destructive testing by ANSYS. The results consist of finding damages and time domain curves. Besides, delamination analysis is performed.

Time range is adjusted from 5X for 104 seconds to 0.1 seconds. Displacement response is documented. Different damage locations with different types of materials and vibrations are analyzed. The results are indicated valuable technical evaluations.

This work is carried out to find the fracture location. The small part of the structure is examined. The whole structure analysis is required in industrial applications. Time domains and frequency plots have wide applications in preventive maintenance and condition monitoring systems.

There are many factors that are concerned with fractures. Dynamic analysis is performed successfully for variety of materials. Dynamic time plots were extended to higher time values. Besides, delamination in composite structures could be evaluated in dynamic time plots.

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