

Dynamic behavior of cracked ceramic reinforced aluminum composite beam

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(Received January 30, 2020, Revised November 16, 2021, Accepted December 20, 2021)

Abstract. This paper presents the vibration analysis of cracked ceramic-reinforced aluminum composite beams by using a method based on changes in modal strain energy. The crack is considered to be straight. The effective properties of composite materials of the beams are estimated through Mori-Tanaka micromechanical model. Comparison study and numerical simulations with various parameters; ceramic volume fraction, reinforcement aspect ratio, ratio of the reinforcement Young's modulus to the matrix Young's modulus and ratio of the reinforcement density to the matrix density are taken into investigation. Results demonstrate the pronounced effects of these parameters on intact and cracked ceramic aluminum beams.

Keywords: aluminum; ceramic; composite beam; crack; vibration

1. Introduction

Extensive research is being carried out to develop high performance composite materials that can meet the demands of commercial applications. Ceramic reinforced Aluminum composites have superior properties; high specific strength, high toughness and corrosion resistance, good thermophysical and tribological properties, low density, high abrasion, wear resistance and damping capabilities (Patel *et al.* 2011, Inegbenebor *et al.* 2015, Suthar and Patel 2018, Tlidji *et al.* 2019). Thanks to their exceptional properties, ceramic reinforced Aluminum are widely used in aerospace, automobiles as well as in military and electronics applications, high-tech structural and functional applications including thermal management areas (Inegbenebor *et al.* 2015, Suthar and Patel 2018).

The most commonly used ceramic reinforcement is Aluminium Oxide (Al_2O_3) known as alumina (Ramnath *et al.* 2014, Mohammed *et al.* 2021). It has ultrahigh thermal stability and mechanical strength, good compressive strength and wear resistance. It is chemically stable, inert and non reactive at high temperatures.

Intensive investigations concerning ceramic reinforced aluminum have been published in recent decades. Rahimian *et al.* (2011) have deduced that the wear properties of Aluminum Oxide reinforced Aluminum (Al_2O_3/Al) composites is improved by selecting proper sintering parameters. Tatar and Ozdemir (2010) have studied the improvement of thermal conductivity of Al_2O_3/Al composites with different alumina content. Kok (2005) used the vortex method to fabricate the Al_2O_3 reinforced Al-alloy composites. He has studied their mechanical properties and found the optimum conditions of the production. The

wettability and the bonding between Al-alloy particles were improved by applied pressure. Abouelmagd (2004) studied the hot deformation and wear resistance of powder metallurgy aluminum metal matrix composites. It was found that the addition of Al_2O_3 increases the hardness and compressive strength. The fatigue behavior of the pure Aluminum reinforced with Al_2O_3 fibers was investigated by Ding *et al.* (2003). They found that the predicted fatigue lives coincide with the observed fatigue lives over a wide range of strain amplitudes for a wide range of test temperatures. The behavior of 6061 aluminum alloy and 6061 aluminum alloy reinforced with short Al_2O_3 fibers is studied by Ding *et al.* (2002). They conclude that the addition of the reinforcement will not only strengthen the microstructure of aluminum alloy, but also the channel deformation at the tip of a crack into the matrix regions between the fibers. Fu *et al.* (2004) investigated the wear properties of Saffil/ Al_2O_3/Al . Under dry sliding condition, high temperature and high load, Saffil/ Al_2O_3/Al showed good wear resistance.

In recent years, ceramic reinforced Aluminum has been extensively used in major engineering structures mainly due to its high mechanical and physical properties (Meksi *et al.* 2019). However, during the service live these composites are threatened by cracks which could be caused by operational loading, aging, chemical attack, mechanical vibration, changing of ambient conditions and shock etc. Hence, the dynamic analysis of structures made of Aluminum composites is a key point in the design procedure.

The fracture behavior of aluminum metal matrix composites depends on the distribution of particulates in the matrix. The non-uniform distribution of particulates in the matrix reduces the strength level (Duan *et al.* 2018). The final properties of metal matrix composites depend on the interface strength between the matrix and reinforcement (Seifi and Khoda-yari 2011). Many other manufacturing

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variables affect the final properties of Al₂O₃/Al composites; matrix alloy, heat treatment condition, reinforcement content and size (Rahbar-Ranji and Zarookian 2015, Ait Yahia *et al.* 2018, Khiloun *et al.* 2019). Xing *et al.* (2013) investigated the dynamic fracture behaviors of the extruded aluminum alloys by using an instrumented drop tower machine. They pointed out that both the initiation toughness and the propagation toughness increase with the loading rate. Further, the difference between the fracture toughness behaviors is found to be dependent on the variation of fracture mechanism. Different loading conditions are applied by Pedersen *et al.* (2011) in order to identify the fracture mechanisms of aluminum alloy. They discussed the influence of stress triaxiality on its fracture behavior through the introduction of a notch in the tensile specimen. Han *et al.* (2011) studied the effects of the pre-stretching and aging on the strength and fracture toughness of 7050 aluminum alloy. The results show that the peak-aged 7050 aluminum alloy possesses a higher strength, but its fracture toughness is poor. Hu *et al.* (2015) carried a series of vibration fatigue tests on aluminum alloy 2024 cantilever beam in order to explore the effect of excitation frequency on vibration fatigue lives. The longest-life vibration fatigue of cantilever beam was appearing and the least fatigue failure region of fracture surface was found when the excitation frequency is equal to the natural frequency of the sample. Hu *et al.* (2013) performed the vibration fatigue experiments of cantilever beam structures to investigate the fatigue behavior of 2024-T62 aluminum alloy. The fatigue damage was calculated. The results were in accord with the reduction of the natural frequency measured in experiment. The effect of vibration state on the vibration fatigue behavior of the cantilever beam was discussed. Based on the transfer matrix method, Wang *et al.* (2012) investigated the variation of the natural frequency of a simply supported beam with single crack under high temperature. Yang *et al.* (2017) predicts the fatigue crack growth of 7075 aluminum alloy. They have deduced that the presence of the crack not only changes the regional stress and strain fields of the crack tip but also affects structural dynamics.

There are different issues that have yet to be solved. One of them is examining the natural frequencies of cracked Al₂O₃/Al composite beams taking into account the effect of reinforcement Young's modulus, density, volume fraction and aspect ratio.

Based on this motivation, this work is conducted to investigate the effect of the reinforcement mechanical and geometrical characteristics on the dynamic behavior of cracked Al₂O₃/Al composite beams.

The paper has the following outline. In section 2, the homogenized properties of Al₂O₃/Al composites are predicted using the Mori-Tanaka homogenization method. Section 3 details the modal strain energy based method. Section 4 presents the numerical results of free vibration of cantilever Al₂O₃/Al composite beams. The effect of the reinforcement geometrical and mechanical properties on the dynamic behavior of intact and cracked composite beams is discussed on the same section 4. Conclusions are exposed in section 5.

2. Mechanical properties of Al₂O₃/Aluminum composite material

2.1 Introduction

The Mori-Tanaka micromechanical approach approximates the interaction between the phases by assuming that each inclusion is embedded, in turn, in an infinite matrix that is remotely loaded by the average matrix strain or average matrix stress, respectively. The Mori-Tanaka method is selected due to its successful application to diverse heterogeneous material systems. It is a powerful tool for modeling multi-phase materials as well as it gives fairly good predictions of the composite stiffness (Mori and Tanaka 1973, Benveniste 1987).

Here we assume that the composite is comprised of two phases; the Aluminum matrix with a corresponding stiffness C_m and volume fraction V_m while the Alumina fiber phase has a stiffness C_r and a volume fraction V_r .

Following the standard Mori-Tanaka derivation, the expression for the dilute strain-concentration factor is given as

$$A = [I + SC_m^{-1} \cdot (C_r - C_m)]^{-1} \quad (1)$$

Where I is the fourth order identity tensor and S is the standard Eshelby tensor. The effective composite stiffness C is given as follow

$$C = C_m + V_r \langle (C_r - C_m) \cdot A \rangle \cdot [V_m I + V_r \langle A \rangle]^{-1} \quad (2)$$

where $\langle \cdot \rangle$ represent the orientational average.

2.2 Al₂O₃/Al composite

For the purpose of comparison, the Young's modulus and Poisson's ratio of Al₂O₃ reinforced aluminum and aluminum alloys composites have been estimated by means of Mori-Tanaka homogenization method.

The Young's modulus of AlSi alloys and Al₂O₃ reinforced AlSi composites were measured by means of a TA Instruments DMA 2980TM dynamic mechanical analyzer (Fernando 2010).

In this section 20% volume fraction of Al₂O₃ incorporated in the AlSiX is investigated; see Table 1 for the properties (Fernando 2010). Young's modulus of 3D randomly oriented Al₂O₃/AlSiX composites with short reinforcements (aspect ratio = 17) are reported in Table 2.

Table 1 Young's modulus and Poisson's ratio of alloys and composites

Components	E (GPa)	ν
Al	69	0,33
Al ₂ O ₃	370	0,22
AlSi12(AC)	77	0,33
AlSi12(ST)	75	0,33
AlSi18(AC)	84	0,33
AlSi18(ST)	82,5	0,33

Table 2 Experimental data

Composites	E(GPa)
AlSi1/Al ₂ O ₃	91
AlSi12/ Al ₂ O ₃ (AC)	97
AlSi12/ Al ₂ O ₃ (ST)	92
AlSi18/ Al ₂ O ₃ (AC)	106
AlSi18/ Al ₂ O ₃ (ST)	99

From Table 2, it is seen that the modulus of the Al₂O₃/Al composites is 1.3 times higher than that of Aluminum.

3. Modal strain energy based method

Fig. 1 shows an Euler-Bernoulli cantilever beam of length, L, height, H, and width B, containing an edge crack of depth, a, and located at the position, L₁, from the fixed support. The crack is supposed to remain open during vibrations. The Young's modulus, the Poisson's ratio and the mass density of Al₂O₃/Al composite materials are respectively denoted by, E, ρ and ν.

For the convenience of deduction and calculation, the dimensionless parameters are defined

$$u = x/L, \quad h = H/L, \quad b = B/L, \quad \alpha = a/H, \quad e = L_1/L$$

Assuming no volume changes due to the crack, the fractional changes in modal strain energy can be related to the fractional changes in frequency as proposed by Gudmundson (1982)

$$f_{ci}^2 = f_i^2 \left(1 - \frac{\Delta MSE_i}{MSE_i} \right) \quad (3)$$

where f_i and f_{ci} are the angular eigenfrequencies before and after the crack occurrence, and the subscript, i, denotes the ith mode.

For Euler-Bernoulli beam theory, the ith modal strain energy MSE_i can be written as Kim and Stubbs (2003)

$$MSE_i = \frac{1}{2} E \left(\frac{bh^3}{12} \right) \int_0^1 [\phi_i''(u)]^2 du \quad (4)$$

where ϕ_i is the ith mode shape.

The energy loss rate of the ith modal strain energy is (Anderson 2005)

$$\frac{\partial(\Delta MSE_i)}{\partial a} = B \frac{(1 - \nu^2)}{E} K_I^2 \quad (5)$$

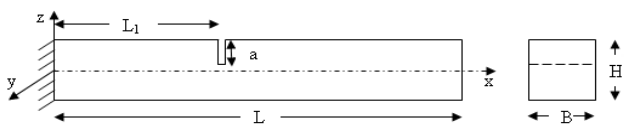


Fig. 1 An Euler-Bernoulli cantilever beam model with an edge crack

The stress intensity factor KI can be given as (Chondros et al. 1998)

$$K_I = \sigma \sqrt{\pi a} F_I(\alpha) \quad (6)$$

The term F_i(α) is a geometrical factor depending on α (Kim and Stubbs 2003)

$$F_I(\alpha) = 1.122 - 1.40\alpha + 7.33\alpha^2 - 13.08\alpha^3 + 14\alpha^4 \quad (7)$$

The stress level is given by

$$\sigma(u) = \frac{1}{2} E h \phi_i'' \quad (8)$$

Substituting Eqs. (6)-(8) into Eq. (5), the developed expression of the decrease of modal strain energy is

$$\Delta MSE_i = \left(\frac{(1 - \nu^2) E b h^4 \pi \alpha^2 F_I^2(\alpha)}{8} \right) [\phi_i''(u)]^2 \Big|_{u=e} \quad (9)$$

From Eqs. (4) and (9), the following equation can be derived

$$\begin{aligned} \frac{\Delta MSE_i}{MSE_i} &= 3h\pi\alpha^2(1 - \nu^2)F_I^2(\alpha) \frac{[\phi_i''(u)]^2 \Big|_{u=e}}{\int_0^1 [\phi_i''(u)]^2 du} \\ &= \frac{3(1 - \nu^2)H\pi\alpha^2 F_I^2(\alpha)}{L} \frac{[\phi_i''(u)]^2 \Big|_{u=e}}{\int_0^1 [\phi_i''(u)]^2 du} \end{aligned} \quad (10)$$

Knowing the fractional changes in modal strain energy, the angular eigenfrequencies after the crack occurrence can be gotten from Eq. (1).

The mode shape of an Euler-Bernoulli cantilever beam is given as

$$\phi_i = c_i [\sin(\beta_i u) - \sinh(\beta_i u)] + \cos(\beta_i u) - \cosh(\beta_i u) \quad (11)$$

With β₁ = 1.875104, β₂ = 4.69409, β_i = (i - 1/2)π and c_i = $\frac{\sin(\beta_i) - \sinh(\beta_i)}{\cos(\beta_i) + \cosh(\beta_i)}$.

4. Numerical results

In the design of a cracked structural element subjected to vibrational loading, it is very important to take perform a dynamic study in order to reduce the effect of crack. This section illustrates the influence of ceramic volume fraction and its aspect ratio on the natural frequencies of ceramic reinforced aluminum Alloy composites.

The method described in the previous section has been applied to a cantilever cracked Euler Bernoulli beam, as shown in Fig. 1, in which the dimensions are chosen as: B = 35 cm and H = 70 cm. The properties of Aluminum metal used in this study are E_m = 70 GPa, ν_m = 0.33 kg/m³. The properties of Ceramic (Al₂O₃) E_r = 380 GPa and ν_c = 0.23 (Pradhan and Chakraverty 2014). Four aspect ratios are considered; A_r = 30, 40, 50 and 60.

The variation of the normalized first three natural frequencies, ω_n/ω_{n0}, of the intact and cracked composite

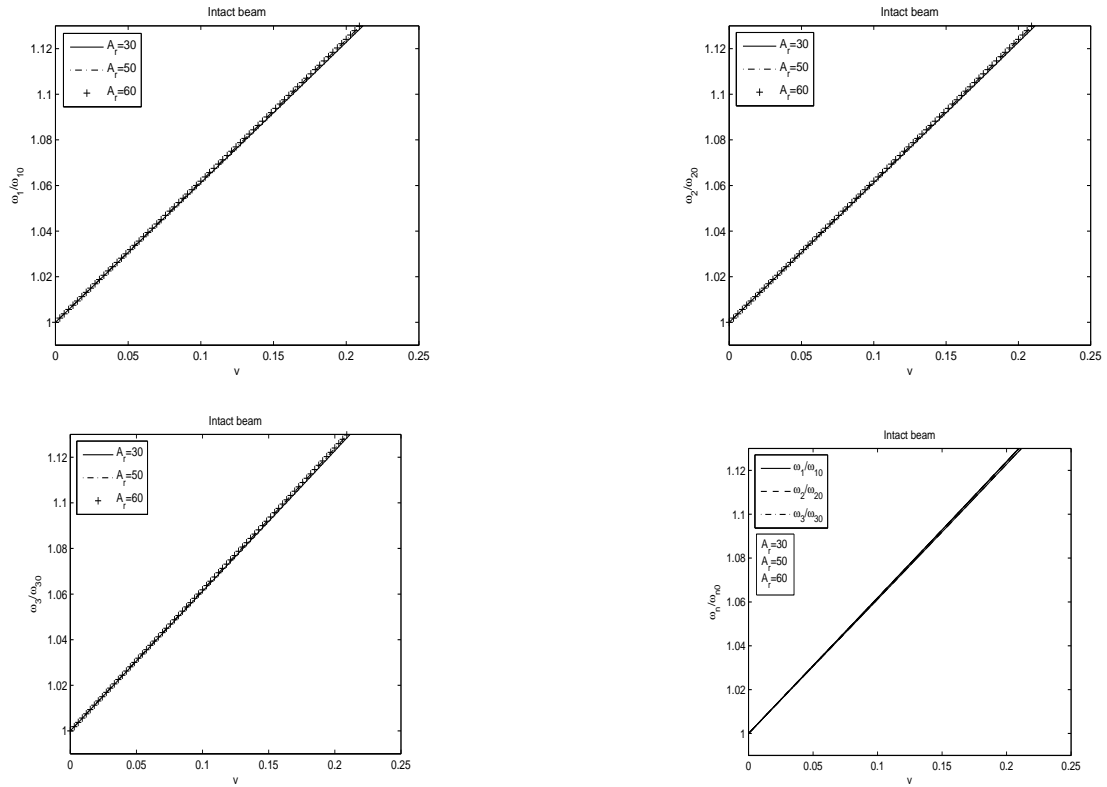


Fig. 2 Variation of the first three normalized frequencies of intact $\text{Al}_2\text{O}_3/\text{Al}$ composite beams as a function of the Al_2O_3 volume fraction

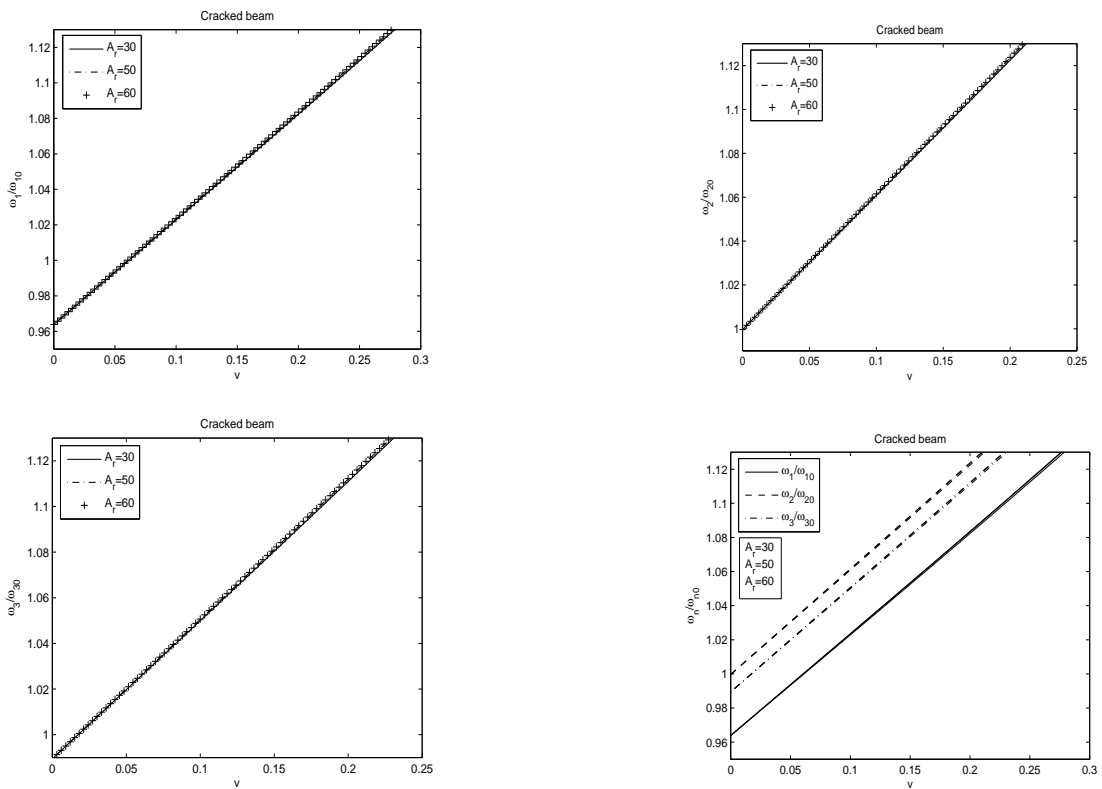


Fig. 3 Variation of the first three normalized frequencies of cracked $\text{Al}_2\text{O}_3/\text{Al}$ composite beams as a function of the Al_2O_3 volume fraction

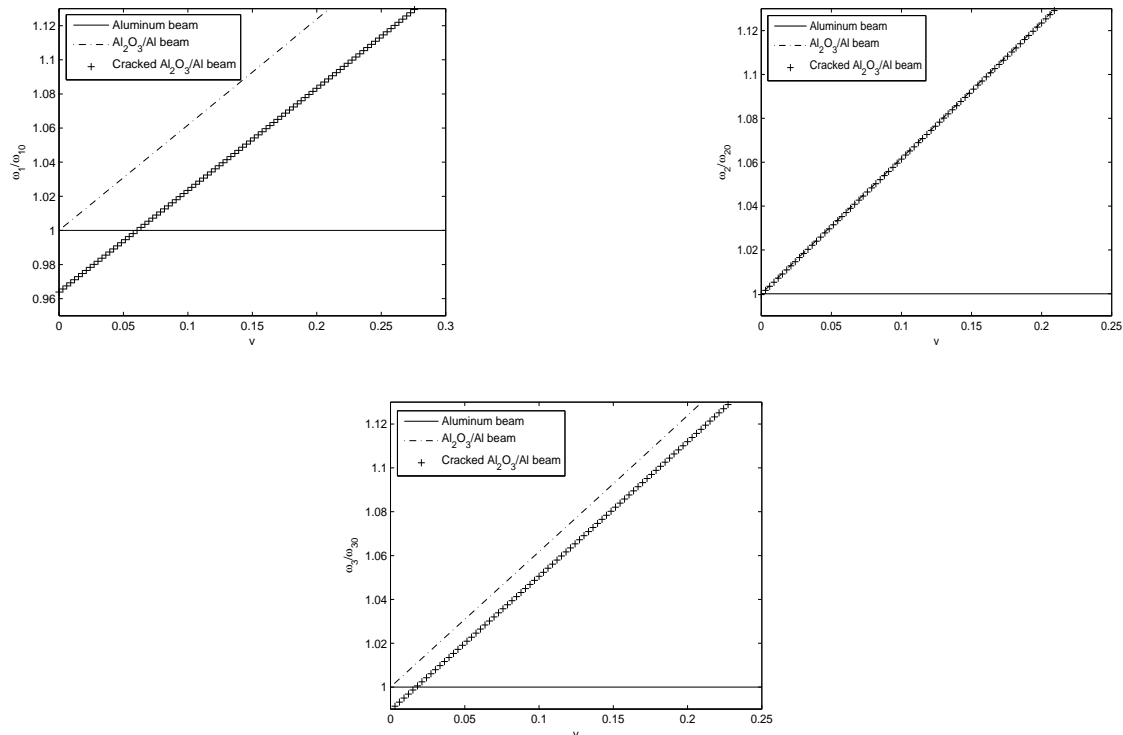


Fig. 4 Variation of the first three normalized frequencies as a function of the volume fraction for $A_r = 50$

beams as a function of the reinforcement volume fraction on the first three normalized natural frequencies of intact and cracked composite beams are shown in Fig. 2.

From Fig. 2, it is deduced that the effective Young's modulus increases linearly with the reinforcement volume fraction. The reinforcing effect of Al_2O_3 is very important and as the Al_2O_3 content in the Aluminum increases, the Young's modulus increases rapidly. For an Aluminum comprising 0.48% of Al_2O_3 , the Young's modulus of the composite is increased by a factor of 1.4. From Figs. 2-4, one can conclude that the vibration of intact and cracked composite beams have one property in common, namely that the three natural frequencies increases linearly with Al_2O_3 volume fraction for any aspect ratio.

With regard to the influence of aspect ratio on the composite Young's modulus and natural frequencies, the investigation has shown (see Figs. 2-4) that short fibers have negligible effect.

Figs. 2(d) and 3(d) demonstrate that the reinforcement volume fraction has the same effect on the three first natural frequencies of intact composite beams and act differently on the natural frequencies of cracked composite beams.

The negative effect of crack on natural frequencies can be compensated by 8% volume fraction of short Al_2O_3 .

Fig. 4 plots the evolution of the first three natural frequencies of Al, intact Al_2O_3/Al and cracked Al_2O_3/Al beams.

It is remarkable that the crack can reduce the natural frequencies of Al beams by 4%. This reduction can be recovered by incorporation of 6% of short Al_2O_3 .

The property in common for the vibration of intact and cracked composite beams is the linearity of the variation of

the three natural frequencies as a function of Al_2O_3 volume fraction for any aspect ratio.

One can clearly distinguish the influence of small aspect ratio ($A_r = 30$) on the natural frequencies from those of relatively high values ($A_r = 50$ and $A_r = 60$).

5. Conclusions

Free vibration analysis of intact and cracked ceramic reinforced aluminum composite beams was studied using a method based on changes in modal strain energy. The Mori-Tanaka homogenization method was used to predict the mechanical properties of the composite materials. Improving the dynamic characteristics of cracked Aluminum beams is achieved by reinforcing with ceramic. Reinforcement with ceramic allows a significant increase of the Aluminum dynamic properties. The improvement of the natural frequencies of cracked beams was attained by increasing the amount of the reinforcement and increasing the slenderness ratio.

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