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Experimental and numerical temperature distribution study for harmonic vibration beam with and without crack effect

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Abstract
In this study, investigation the temperature distribution of vibration beam under force harmonic load applied with force frequency equal to (0.9 from beam natural frequency). Where, the investigation included study the effect of crack depth and position on the temperature distribution in the beam. There, the beam investigating made of carbon steel materials and supported with various boundary condition. In addition, the investigation included using experimental and numerical technique to calculate the temperature of beam with crack and uncrack effect, with various depth and position crack influence. Therefore, the experimental technique included building of rig vibration and applying to harmonic load on the beam, supported with various boundary condition, and then, measurement the temperature in the beam by using thermal camera. Also, the numerical technique included calculated same variable evaluated by experimental technique with same parameters effect, by using finite element method with using of COMSOL program, and then, calculate the change in the temperatures that appeared in the numerical solution and compare them with the change in the calculated temperatures in experimental work. Therefore, the comparison of results shown that the experimental and numerical results are agreement with maximum error about (10.8%). Where, the results shown that the temperature change with crack beam more than the temperature change of beam without crack, for various beam boundary conditions supported. In addition, the results shown that the time required to stability the change of temperature, due to applied harmonic load, increase for beam with crack effect.

Keywords: Heat induce vibration; Heat generation crack structure; Crack beam vibration; Harmonic vibration; CFD heat vibration; Finite element vibration heat generation.

1. Introduction

The vibrations are basic and fundamental portion of our daily lives for environment engineering today, as it occur in different engineering applications such as vehicles, aeronautics, structures, machines, electronic apparatuses, electric motors, satellites and so forth. At the point when a system or framework is vibrating under the influence of higher frequencies which lead to higher deflection, higher displacement, heat generation and noise. Hence it is necessary to examine these influences of vibrations to enhance the stability of machines and motors. It is necessary to study the temperature distribution and heat generation by the vibration when approaching the resonance state and its influence on the natural frequency as each material has its own internal damping function that works against vibrations. Most of the heat generation by vibration due to the loss of vibration energy resulting from the internal damping system. Where anybody is vibrating under resonant provisos, the loss of energy occurs due to its internal damping properties of the body's material. Internal loss is known here by Hysteresis damped. When a material is unloaded and loaded, the stress-strain due to this unloading and loading follows a different way. This is because of the loss factor which exists as property of any material, which is defined as the ratio of loss modulus to storage modulus. The magnitude of energy lost by the vibration of this body through the internal damping dissipated as heat generation, [1].

Many engineering components used in the aeronautical, aerospace and naval construction industries are considered by designers as vibrating structures, operating under a large number of random cyclic stresses. Consequently, it is natural to expect that fatigue crack initiation and propagation in critically stressed zones of such structures, in particular when local or general resonance occurs. The importance of the beam and its engineering applications is obvious, and it undergoes many different of loading. Many types of loading may cause cracks in the beam. These cracks and their locations effect on the shapes and values of the beam frequency. Recently these topics are so prevailing in the industry of spacecraft, airplanes, wind turbines, turbines, robot arm and many other applications, [2-5]. The cracked structures dynamics have been a subject of interest and research. When a structural origin of the cracks was exposed, the materials intensity and stiffness are reduced, and so reducing natural frequency. The dynamic behavior of cracked structures had been researched through many analytical, numerical and experimental methods and the influence of crack in moving load on machines, instruments and structures is an important problem in the field of engineering and its applications, [6, 7].

Many important studies discussed the influence of crack depth and position on forced vibration for beam structure. Other important studies focused on heat generation as a result of vibration. While this subject is one of the main things especially in dynamic science and for any moving part. There are number of researchers who have studied and reached an equation that links the relationship of heat generation by vibration and its effect on natural frequency. Together, there are researchers who have studied crack influences with a wide range especially in vibration beam, as,

Firstly, at 1980, S. Panteliou et. al., [8], studied the torsional vibrating of rotation shafts can produce significant temperatures by virtue of heat generating from substances damping in the shaft. It had been recently noticed that such a case in electric generators could prompt insulation disappointments and machine blackouts. The trouble of heat diffusion and propagation by virtue of torsional vibrating of rotation shafts has been analyzed in this research. Both plastic deformation losses and material damping have been regarded. The equation of heat conduction has been explained the temperatures of shaft calculated. Modelling charts were given for the calculation of the maximum and higher shaft temperatures and the maximum and higher temperatures as elements of the (Bi.no.) Biot number. It is demonstrated that coefficients of little heat transfer on the shaft surface can prompt to very highly surface temperatures. Also high diameter across to length proportions likewise prompt to highly temperatures.

Then, at 2010, R. Ganesan et. al., [1], studied temperature distribution and heat generation is examined for longitudinal vibration beam at its resonance conditions. They showed the temperature distribution and heat generation demonstrates a bigger value and a greater premium at the node location when contrasted with the other part or other position of the beam because of, the beam isn't permitted to movement free under resonance conditions in the node position. After this, at 2011, H. M. Youssef et. al., [9], presented the vibration characteristics and qualities of the temperature, the deflection, the displacement, the strain energy and the stress of an Euler Bernoulli beam initiated by a ramp kind heating. An analytical technique and numerical method depended on the L.T. (Laplace transformation) has been utilized to compute the vibration of the temperature, the deflection, the displacement, the strain energy and the stress. The influences of the relaxing time and the ramp time parameter onto every the studiedly domains have been displayed and instantiated graphically.

Then, at 2016, A. K. Jebur, [10], researched the heat generation in the beam sample exposed to little vibrations to uncover the elastic viscos behaviour under vibration and heat influence. The sample calculated addition thermal structural interacting. The outcomes acquired from analyzing of the sample treatment by the (FEM) finite element method using COMSOL program, to compute magnitude of a heat generation in the substance. Then, the transfer analysis of a transient heat emulated the tardy rising temperature utilizing heat source conditions in the beam. The sample had been structured from two blocks, the first block from Aluminum while the another block made from β–Titanium.

At, 2018, D. H. J. Al-Zubaidi et. al., [11], investigated the effect different harmonic frequency load on the heat generation of different supported beam structure. Where, the investigation included used analytical investigation to calculated the value of heat generation in beam with force vibration effect. There, the analytical solution included drive of general equation of motion for force harmonic vibration beam, and then, calculated the deflection response for beam ,and finally, calculated the heat generation due to harmonic load applied. In addition, the study included using numerical technique by using finite element method to calculated the heat generation in beam, and then comparison the results with analytical result. Finally, at 2019, D. H. J. Al-Zubaidi et. al., [12], investigated the effect of crack depth and position on the heat generation for various supported beam structure. Where, the study included used for the analytical and numerical technique to calculate the heat generation in beam, due to harmonic load vibration, with various crack effect. Where, the investigation included drive for the general equation of motion for beam with different crack parameters effect, and then, calculated the heat generation with crack effect. In addition, comparison the analytical results with numerical results. Where, the numerical results were calculated by using finite element method, with using of COMSOL program.
From the previous researches, it was shown that some researches concentrated on the heat generation as a result of vibration, another section will find the crack influence on the beam vibration particularly from the point of view of analytical. So, the current research is guided to development of previous research in addition to influence of crack depth and position on temperature change due to forced vibration for beam structure, with various boundary conditions. So the change of the temperatures to prove the correctness of the numerical solution will be compared with an experimental results, and to know the accuracy of this research and its results, with the influence of crack depth and position.

2. Experimental work

The main apparatus of the system working and devices utilized to find the temperature change in the beam is explained by the vibration of the beam. Several cases have been taken for the purpose of studying the effect of crack on temperature and natural frequency. The main parts used in experimental work are the Universal Vibration device is used and the thermal camera, as shown in Figure 1.

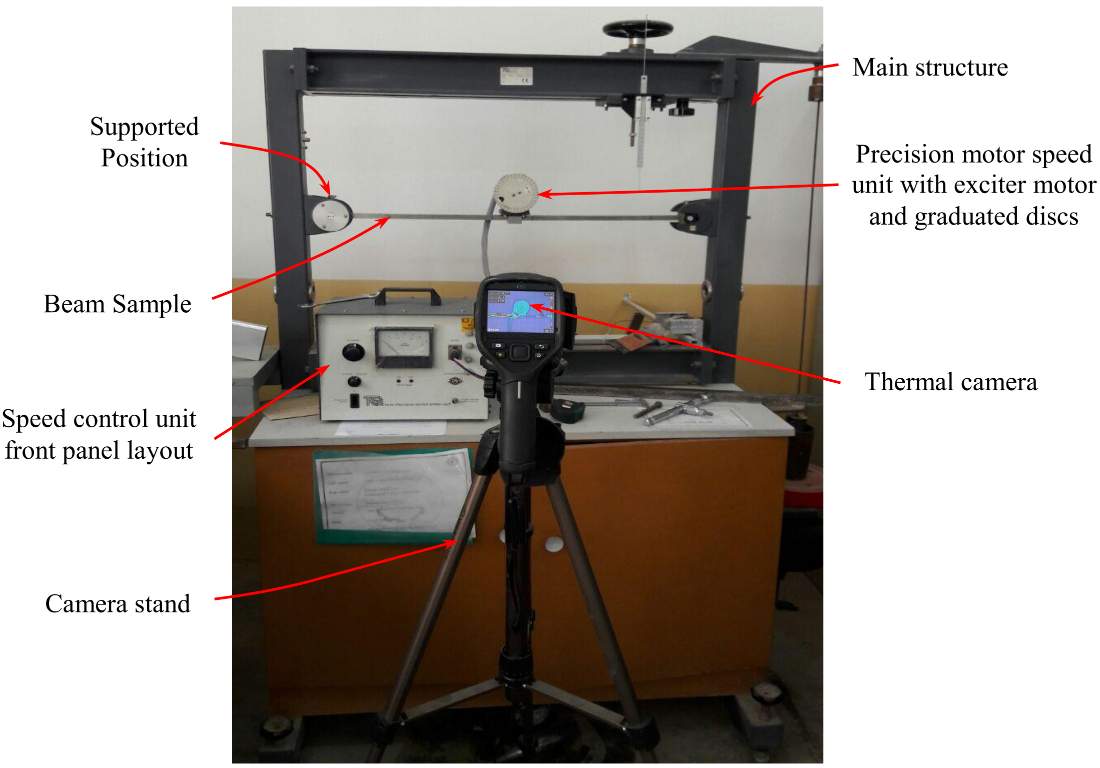
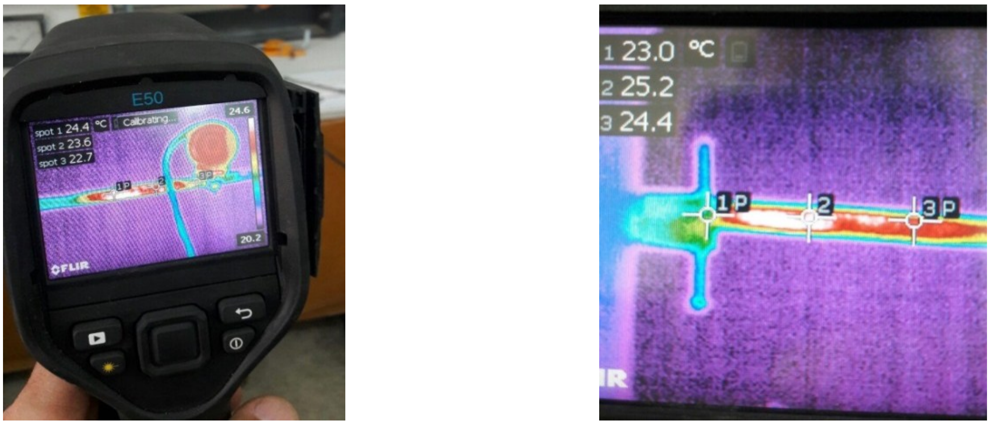


Figure 1. The test rig and some of the equipment and devices used in the examining work.

The test rig and some of the equipment and devices used in the examining practical are,

1. The steel beam: because it was used for the appearance of heat in a clear manner in addition to its availability in the local markets according to the required sections, the models were taken with a cross section $(2.5\ cm\ * 2.5\ cm)$ and length $(84\ cm)$ according to the specifications of the device used to allow the use of models of this length, the beam samples were made of high carbon steel (1.5% carbon). The beam specification used was calculated the density of the beam, [13, 14], used about $\left(7752\frac{kg}{m^3}\right)$. The modulus of elasticity of the beam was also calculated by using a tensile device, [15-18], and it was found that the modulus of elasticity of the beam, (E ≅ 180 GPa).
2. The precision motor speed unit with exciter motor and graduated discs, it is a device that connects to the beam and works at different speeds up to $(5000\ r.p.m.)$, and there is a circular disc containing a circular hole diameter (1.2 cm) on one side and the center of the hole (4 cm) away from the center of the disk and the hole causes unbalance in the circular disc causing vibration in the beam.
3. Thermal camera FLR E50, as shown in Figure 2, which can give temperature measurement with high accuracy by taking pictures of the beam showing the temperature gradient and during selected time periods and kept in camera memory.



(a) Thermal camera (b) Beam sample temperature measurement

Figure 2. Temperature measurement by thermal camera.

Then, the special test system and connect the devices are shown Figure 1, and the beam is connected to the Universal Vibration device through the supported places and the thermal camera is connected to the stand and at a distance of (1 meter) from the beam. The exciter motor is operated and supplied at a different speed through the speed control unit. The temperature is measured for three types of supported beam with and without crack effect, as follows,

I. Simply supported beam, the above beam was connected to have been shed harmonic force by the precision motor speed unit with exciter motor and graduated discs. It was connected to the middle of the beam for simply supported beam, at different speeds and different frequencies compared to the natural frequency $(\omega = (0.5, \ldots, 1.2)\omega_n)$. The frequency $(\omega = 0.9\omega_n)$ was chosen for comparison because it was near from the biting and resonance state to generate appropriate heat. The temperature is measured using the thermal camera (FLIR E50) as shown in Figure 2, along the length of the beam and different locations for 900 seconds. The readings for the different locations were recorded during this period, for each minute and were scheduled to be compared with the numerical solution. Now, a narrow horizontal crack that is perpendicular to the length of the beam and at a width of approximately (0.7 mm), is made by using the power tool, and the different positions in the beam $(L_c = 0.1, \ldots, 0.74\ m)$ from the place of supported and to depths on the used beam $(dc = 1.25\ cm)$, and the temperature was measured for each case and for equal time periods. It was observed that the maximum temperature change was in the middle and gradually faded by the sides.

II. Clamped beam, same as the previous work but here the method of supported is different where the fixed brackets for the supported of the beam. It have been shed different frequencies relative to the natural frequency, it was also the work of a crack for different depths and locations. It was observed that the maximum temperature change was on the sides, where, the temperature rises in the center but less than the sides.

III. Cantilever beam, also the same as the previous work and the method of supported from a fixed side and the other free side, it was also the work of a crack and different depths and locations. It was observed that the maximum temperature change was on the fixed side gradually decreasing and disappearing at the free side.

Therefore, to obtained on the agreement for experimental results, then, comparison its results, for natural frequency and temperature change calculated, with numerical results, [19-21], which its calculated by using finite element method with using COMSOL program, with effect for various boundary conditions and crack depth $(dc = 1.25\ cm)$ and crack location $(L_c = 0.42\ m)$, for simply supported beam, and $(L_c = 0.1\ m)$, for other supported beam.

3. Numerical technique

The numerical technique included calculated the temperature change in beam with various boundary conditions and crack parameters effect, as presented in experimental work, and then, comparison the results with calculated experimental results to given the agreement for technique used. There, the numerical technique include using finite element method to calculated parameters required, by using COMSOL program. The numerical solution has become widely used in most sciences, especially in engineering applications because of its role in solving many of the problems that are difficult to solve analytically and has a great credit to stand on the obstacles and treatment, [22-24]. The COMSOL program will be used, which will depend on the finite element method (FEM) for design and analysis of the models. It gives the outcomes required by simulations using computer programming to reach the outputs the completion of the research. The development of the mechanism of work, and compared to other outcomes extracted either in the analytical solution or in the experimental work, [25, 26]. The COMSOL program was used to find the change temperature values by the vibration of the beam exposed to the harmonic force at different frequencies for different cases of supported.

The beam design length (84 cm) and cross section $(2.5\ \text{cm} * 2.5\ \text{cm})$ as in the Figure 3, and the material used is carbon steel with a density of $(7752\,\frac{\text{kg}}{\text{m}^3})$ and modulus of elasticity (180 GPa) and temperature surrounding (22 ℃). The supported is determined by the type of beam where the use of three types including (cantilever beam, simply supported beam, clamped beam) and each type of supported has special boundary conditions, the required frequency and force are applied to the beam, after which the program is executed and the desired results and figures are included. The same previous work is repeated but there is a crack in the beam at the depths and locations same presented in experimental work, to know the effect of the crack on the temperatures change. The design of the model form on the mesh as in Figure 4, which follows a finite element method (FEM) to give the results the elements, the results will be more accurate for fine mesh, [27, 28], if the distance between the nearest mesh lines, the mesh was represented symmetrically for all types of supported in case of presence or absence of the crack, so that the accuracy of the results is uniform for all cases to be used in comparison

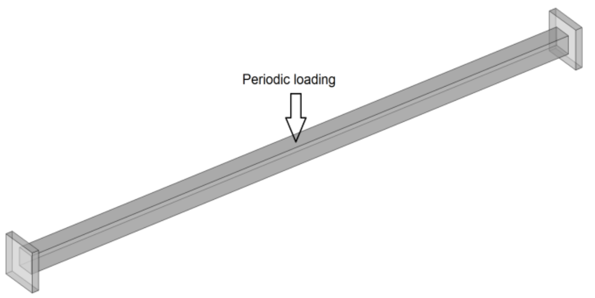


Figure 3. Three-dimensional computational domain.

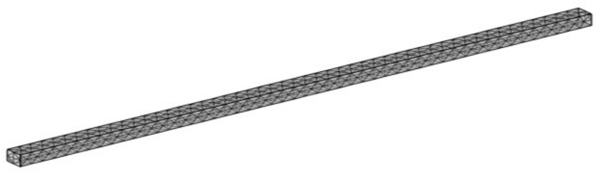


Figure 4. Mesh of the computational domain.

The finite-volume method was used to discretize the governing equations, which are in turn solved using a commercial CFD code having the power to address multi-physics problems (COMSOL v5.3). A computational quadratic mesh has been used in this model. Stringent numerical tests were performed to ensure that the solutions were independent of the grid size. Grid sensitivity has been performed to ensure that the solutions acquired using the selected mesh is independent of the grid size. Different cases are studied for the computer mesh where the comparison is made for the design of the mesh using the

COMSOL program in the absence of a crack in the beam. Also, a computer mesh is designed in the case of a crack in the beam and what is the effect of the crack on the mesh as in Figure 5. And using the finite element method (FEM) where the model is divided into small parts and elements and simple geometric shapes that make it easy to distinguish between the two cases to give different results. Default mesh setups were utilized. The model solution at transient boundaries. It is plotted measured values of displacement, heat generation and the temperature distribution utilizing domain plotting parameters. The Eigen natural frequency analysis outcomes initially then, the resonance are appeared in the distorted shape with sub-domain outcomes. The temperature distribution and heat generation plot outcomes are appeared of normal sub- domain outcomes. The temperature along the beam during a fixed period (60 seconds) as shown in Figure 6 a, b, and c, for different supported beam, it can be noted that the temperature at the fixed end is not highest temperature.

4. Results and discussion

The numerical solution and the experimental work, for the change in temperature by the vibration of the beam exposed to the harmonic force with time whether the presence of crack or absence of it. In the experimental work can be calculating the change in temperature using the thermal camera, so the use of the Comsol program to calculate the magnitude temperature changes in the beam due to vibration, and then comparison the results together. The numerical solution will be implemented using the COMSOL program by designing models similar to the beam specifications in terms of dimensions, geometry and properties of the material used the same forces exerted during vibration of the beam calculated by experimental work with compared between them the change in the calculated temperatures in experimental work. The amount of temperature in the assumed beam (length L = 0.84 m), width and height w = h = 2.5 cm), and made of carbon steel. The natural frequency was calculated experimentally by vibrating the universal vibration (TM16) very high and reading was recorded which was approaching to the natural frequency calculated numerically.

The results for temperature change of beam applied to harmonic load with and without crack effect, and compared for the experimental and numerical solution for different supported beams are presenting in Figs. 7 to 9, as following,

I. For cantilever beam, Figure 7, shows the temperature difference between the local temperature and the initial temperature at constant position and constant load frequency ($\omega = 0.9 \times \omega_n$), as shown in Figure 7a, at fixed bam point, for uncrack beam and Figure 7b for crack beam, at crack location point. Where, the frequency for beam without crack is ($\omega_n = 182.6862\ \frac{rad}{sec}$), and natural frequency for crack beam ($\omega_n = 162.1470\ \frac{rad}{sec}$).

II. For simply supported beam, Figure 8 shows the temperature difference between the local temperature and the initial temperature at constant position and constant frequency ($\omega = 0.9 \times \omega_n$) for beam without crack as shown in Figure 8a, at middle beam point, and for beam with crack effect as shown in Figure 8b, at middle beam point. Where, the natural frequency for beam without crack effect is ($\omega_n = 512.808\ \frac{rad}{sec}$), and the natural frequency for beam with crack effect, at position $L_c = 0.42\ m$ and depth $d_c = 1.25\ cm$, is ($\omega_n = 469.5428\ \frac{rad}{sec}$).

III. For clamped supported beam, Figure 9 shows the temperature difference between the local temperature and the initial temperature at constant position and constant frequency ($\omega = 0.9 \times \omega_n$) for beam without crack as shown in Figure 9a, at fixed beam point, and for beam with crack effect as shown in Figure 9b, at fixed beam point. Where, the natural frequency for beam without crack effect is ($\omega_n = 1162.478\ \frac{rad}{sec}$), and the natural frequency for beam with crack effect, at position $L_c = 0.42\ m$ and depth $d_c = 1.25\ cm$, is ($\omega_n = 1093.309\ \frac{rad}{sec}$).

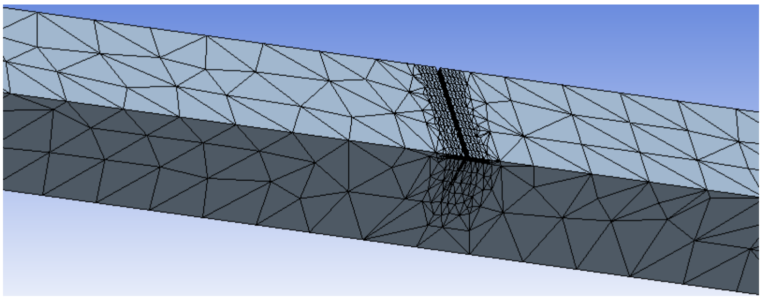
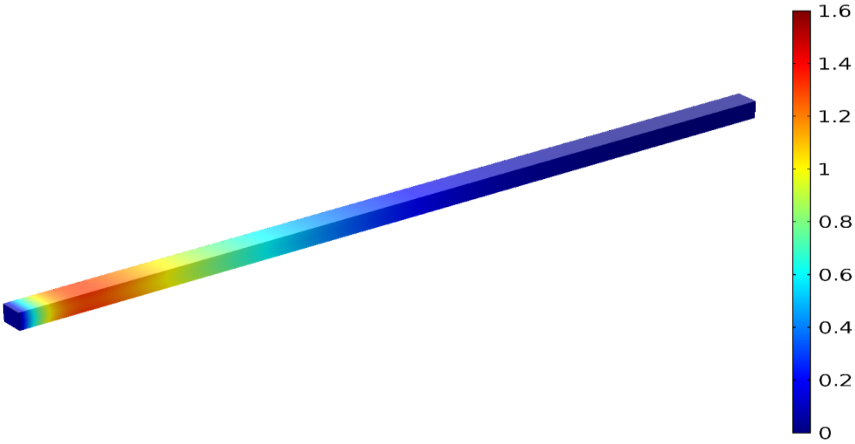
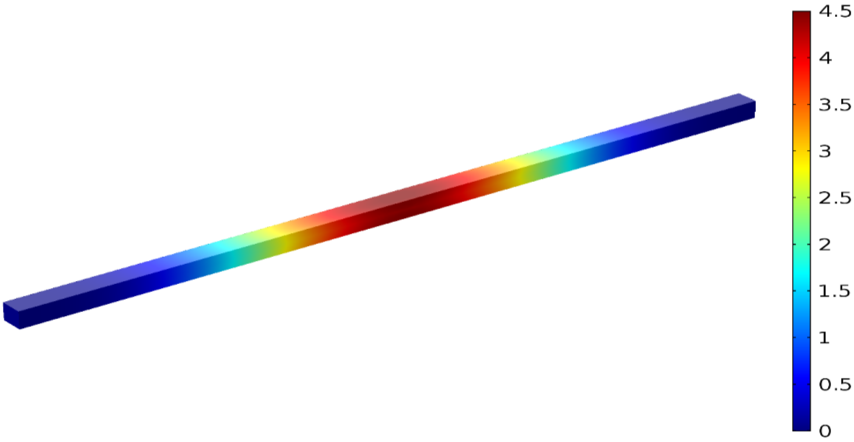


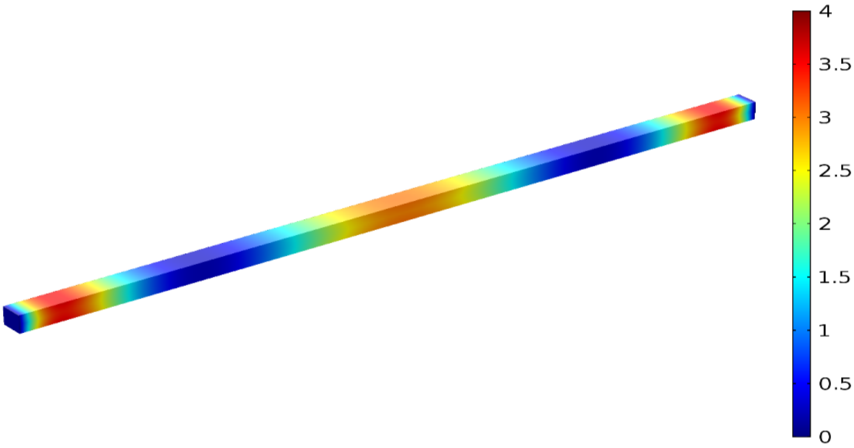
Figure 5. Beam mesh with crack is maximized.



(a) Temperature (°C) contour for cantilever beam.

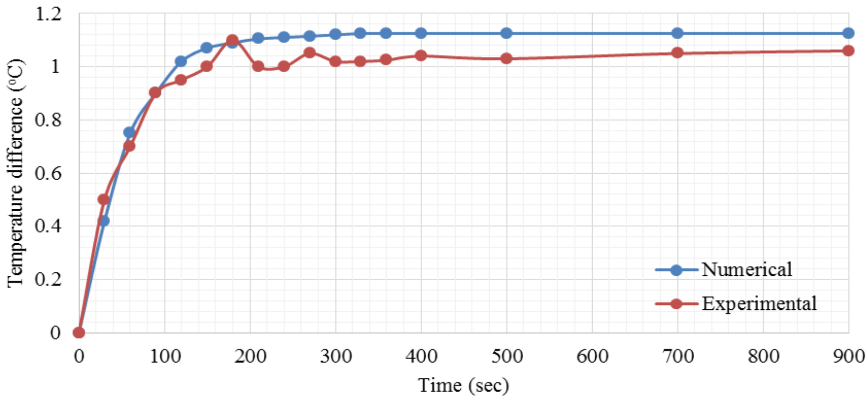


(b) Temperature (°C) contour for simply supported beam.

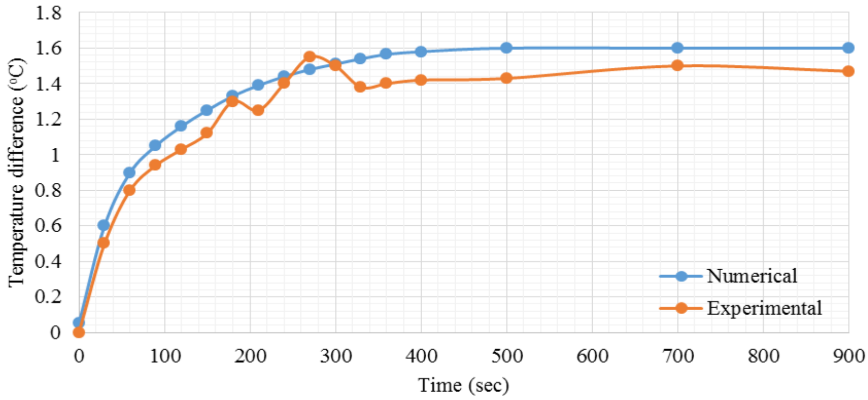


(c) Temperature (°C) contour for clamped beam.

Figure 6. The relationship between the temperature & the length of the beam with constant time.

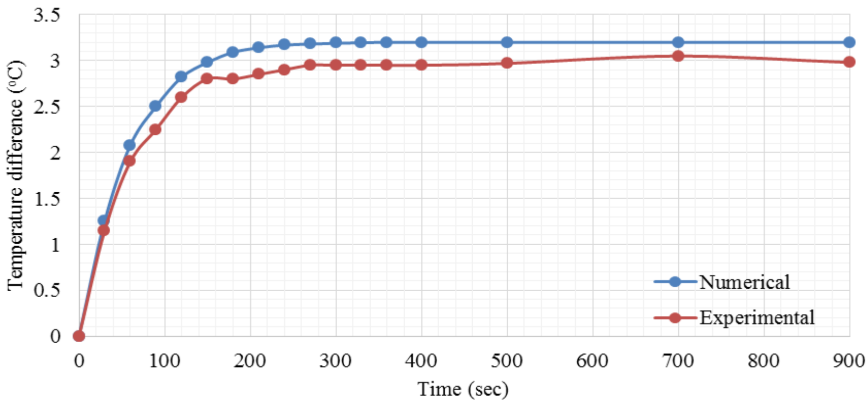


(a) Without crack.

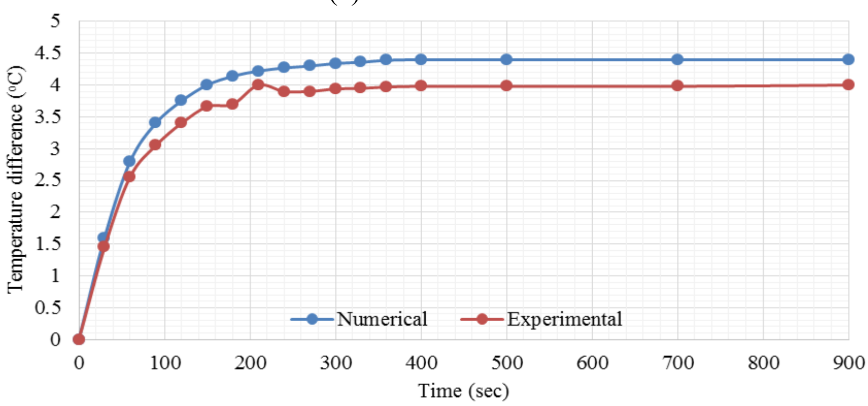


(b) Beam with crack position $L_c = 0.1\ m$, and depth $d_c = 1.25\ cm$.

Figure 7. Experimental and numerical change of temperature for cantilever beam.

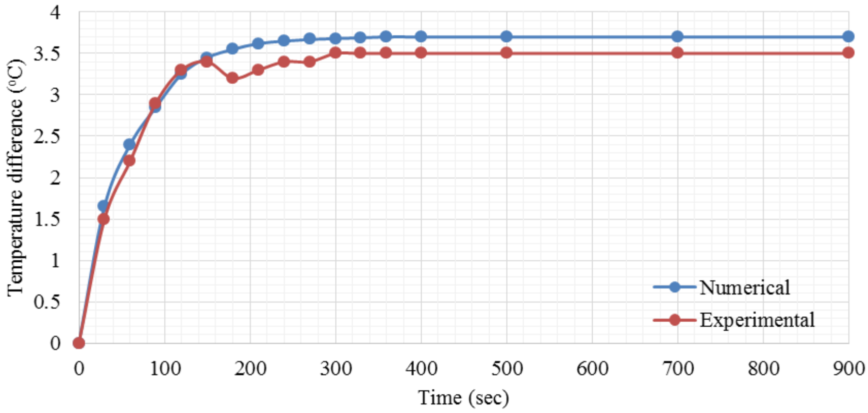


(a) Without crack.

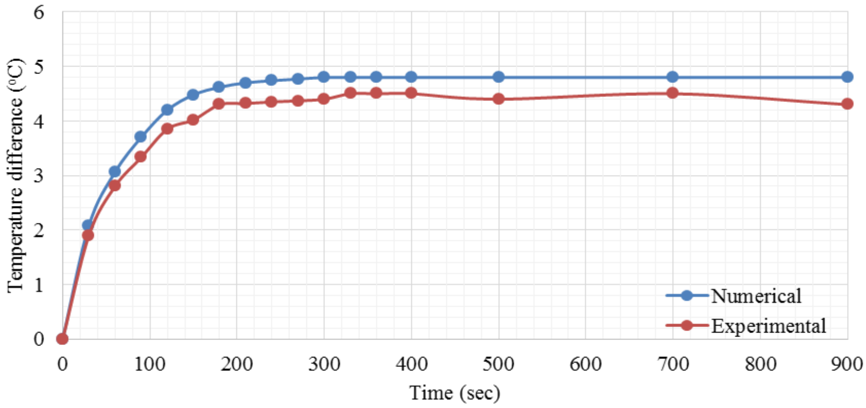


(b) Beam with crack position $L_c = 0.42\ m$, and depth $d_c = 1.25\ cm$.

Figure 8. Experimental and numerical change of temperature for simply supported beam.



(a) Without crack.



(b) Beam with crack position $L_c = 0.42\ m$, and depth $d_c = 1.25\ cm$.

Figure 9. Experimental and Numerical Change of Temperature for Clamped Supported Beam.

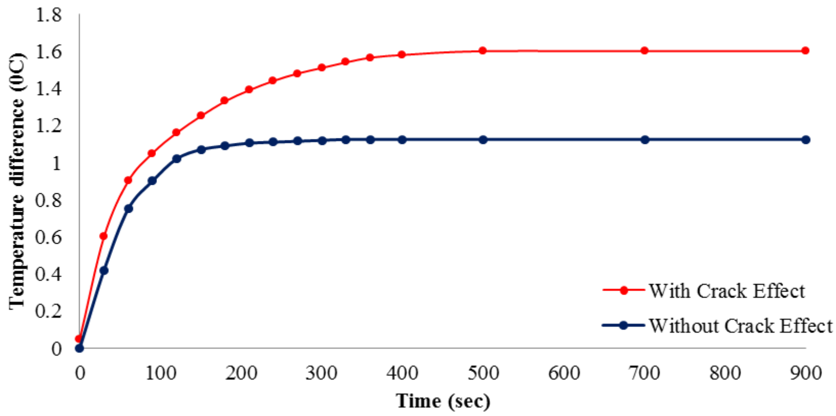
Then, from Figure 10 can be shown that the change of temperature are increase with crack effect for different beam boundary condition, as shown in Figure 10a, for cantilever beam with crack position $L_c = 0.1\ m$ and crack depth $d_c = 1.25\ cm$, Figure 10b, form simply supported beam with crack depth $d_c = 1.25\ cm$ and $L_c = 0.42\ m$ crack position, and Figure 10c, for clamped beam with crack position $L_c = 0.42\ m$ and crack depth $d_c = 1.25\ cm$. There, the crack lead to decrease the cross section area, at crack location, then lead to increase the change of temperature for various beam supported. Also, Figure 11 shown that the change of temperature for clamped beam supported more than the change of temperature on other supported beam, simply supported and cantilever beam, with and without crack effect, as presenting in Figures 11a and 11b, respectively. Its increase for temperature change, with various boundary, due to the high different in natural frequency for beam structure with different beam boundary condition (cantilever, simply supported, and clamped supported).
From the results presented can be shown that the temperature change increasing by decrease the vibration cross section area for structure with different effect, as crack or other effect, as presented in Figure 10. Also, the increasing of temperature change increase with increasing for natural frequency of structure, as shown in Figure 11. But, the natural frequency decrease and the vibration cross section area is decrease, then, the change of temperature, then, depends on the most influential parameter, as shown in Figure 10, since the effect of cross section area is most influence, then the temperature change was increased.

5. Conclusion

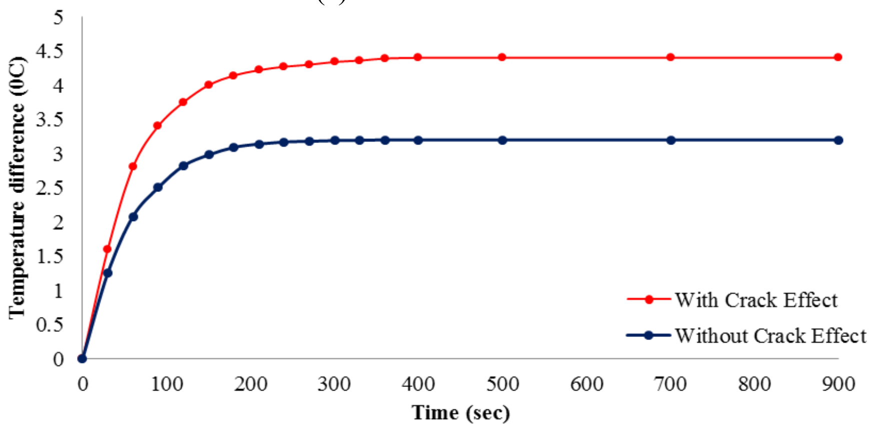
From previous outcomes, the following conclusions can be drawn,

1. The experimental technique is perfect tool can be using to calculated the change of temperature in vibration beam under harmonic load with various harmonic frequency effect of beam with and without crack effect, and with various supported beam.
2. The comparison between experimental and numerical work given a good agreement for temperature change result, for vibration beam under harmonic load, with maximum error did not reach to (10.8%), for different beam boundary conditions and with and without crack effect.

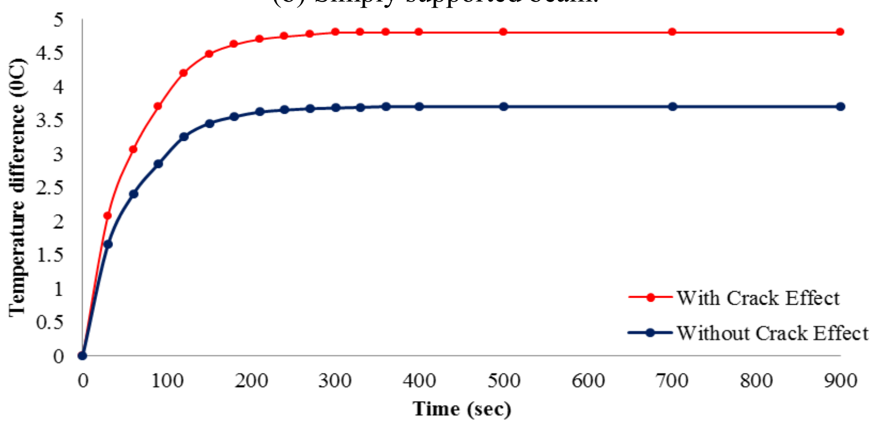
3. The crack lead to decreasing the vibration structure cross section area, and lead to decreasing the moment of inertia of structure, then, the crack lead to increasing the heat generation for beam, and then the crack lead to increase for the change of temperature of beam with various supported.
4. The increasing for natural frequency of beam lead to increase of number of cycle for beam vibration, then, lead to increasing for the change temperature of beam. Therefore, the change of temperature for clamped beam more than the change of temperature for other beam supported.
5. The increasing for change of temperature in beam with various supported, and with effect of crack, depend on the increasing of natural frequency of beam and decrease for vibration cross section area. But, the change of temperature depends on the most influential parameter.
6. The results obtained shown that the maximum temperature change occur at the middle section for simply supported beam, and its change occurred maximum at the fixed section for clamped and cantilever supported beam.



(a) Cantilever beam.

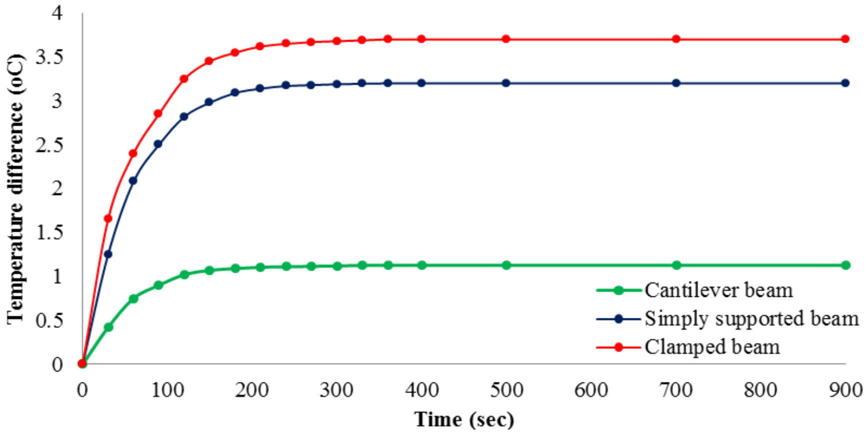


(b) Simply supported beam.

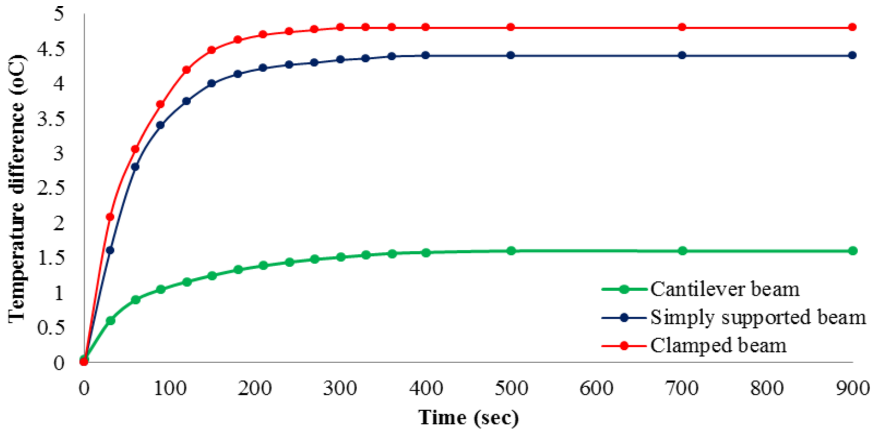


(c) Clamped beam.

Figure 10. Change of temperature in beam with and without crack effect for various boundary condition supported beam.



(a) Without crack effect.



(b) With crack effect.

Figure 11. Change of Temperature in Beam with Various Beam Boundary Conditions Effect.

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