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Research Article

A suggested approach using frequency analysis to detect the damages in reinforced concrete structures

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ABSTRACT

A damaged structure has reduced stiffness due to material and/or some weakened cross-section, and degradation in strength. The motivation for this study is to find out what the distinguishing characteristics in the spectral response of such a structure are during the process of supporting the external load. By applying some tests in both numerical and experimental physical models, which are carefully designed to experience the most representative working conditions concerning controllable and uncontrollable factors, the response of the structure is analyzed extensively for figuring out the typical modes of damages or failure. If the amount of data of the response of a real structure are obtained sufficiently in terms of signals in the time domain and then analyzing them in the frequency domain, the kind of damage could be determined. The structure to be investigated in this study is a simple beam with 1% reinforcement which is deliberately damaged. A numerical model as the pilot test is developed first associated with scenarios of crack positions, symmetric and unsymmetric located damages, low-density. A two-stage strategy including static and vibration tests is suggested. For ensuring the most real condition, some kinds of restraints are altered and assigned into the model for bringing the structure closer to the reality. Results indicate that the variation in the natural frequency of the simply supported beam modeled by SAP2000 is more complicated in the unsymmetric pattens of cracks than that of the symmetric ones; and if the cracks are alternatingly located, the structure still have higher stiffness than that of continuous cracks. Besides, low-density results in a decrease in responsive frequencies from 5 % to 7.2% those in good quality RC structures.

Key words: Damaged structure, Excitation, Low-density material, Responsive frequency, Vibration tests

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INTRODUCTION

Damaged structures require a good prediction conducted by experienced engineers and technologists. There is an urgent demand in the industrial manufacturing process to detect damaged structures to warn and avoid serious casualties in products and supply chains. Once the structure has been damaged, the manufacturing could be failed or stuck, leading to a progressive failure to the overwhelming chain of working, exacerbating the situation, even collapse and causing enormous casualties. As for the structure in civil engineering, the improper diagnose can underestimate the strength of the structure, and worsen the process of load-supporting, re-distributing the internal forces and moments, and increasing the deformation. Even a structural element like a reinforced concrete (RC) beam, failure can be of bending or shearing, or both; the failure due to lack of flexural capacity has specific characteristics, meanwhile, the failure due to shear has a particular shape of cracks. Or a wide flange steel girder, the instability of the web due to the web thickness has no relationship with flexural capacity. It is a kind of local instability, which has a tight relation with the slenderness of the web, instead of global lack of strength. Without an experienced observation via technical diagnose, the damage could not be detected.

Damages in structures as such should be detected and classified in a proper procedure. A weak element in a structure, some structures in buildings or machines, and all the system including structures, etc. should be defined and quantified by numbers, indicators, plots of response, etc. in a detailed program, and reliable reports.

This article suggests ideas for applying a series of tests to improve the process of diagnosing structures from the external configuration to internal conditions for obtaining some basic knowledge about the response of a damaged structure. For some specific pilot purposes, the paper focuses on a basic element, i.e., reinforced concrete simple beam. The target of this study is to establish a foundation for diagnosing a damaged beam in frames. At least the study expects to provide

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a port-folio for fastly assessing the structural system.

METHODOLOGY

In general, the structure has stiffness and strength. The former relates to material and cross-section and the latter, strength of the material. During the process of supporting the gravity static load, the structure deflects and the stress-strain relationship is someway linear or hyperbolic. People can predict the health condition for the structure to the criterion of limit states, i.e. critical limit state, and serviceability limit state. If there is any defect, it is difficult to determine which kind of defects or damages in the structure. No strategy of assessment is created to monitor the structure subjected to static loadings. The mere conclusion is that if the structure deflects too much, it violates the criteria of the serviceability limit state, we conclude the structure lacks stiffness; if the structure develops some cracks, it is predictable the structure comes to the ultimate limit of the cracking moment.

The structure could be assessed by examining more about the change in stiffness and strength by implementing some tests, maybe in the laboratory with a scaled model, or in a numerical model. In the former approach, a design of experiment is developed to account for all the possible conditions of working load exerted on structure; in the latter approach, it should be conducted according to a strategy of testing, in which many different alternatives of loads and effects, both in static and dynamic categories. For evaluating a high stiffness, the characteristics of acceleration are dominant; for a flexible structure, the displacement dominates the response. Besides, the more damages or defects in material, the heavier damping is. It means that damping can be another criterion for assessing the damage in the structure. The more discontinuous in structural configuration, the structure would vibrate to more mode shapes, represented by different frequencies of responses. By analyzing the acceleration and comparing the responsive acceleration to some limit value, it could predict the possibility of cracking, meanwhile, the large deformation in the responsive displacement may originate from the lack of stiffness. The methodology based on dynamics of structure could indicate the response both in the time domain (TD) and frequency domain (FD), and provide a database about all the responses, including frequencies to different mode shapes, acceleration for investigating the cracking possibility, the velocity for computing the impedance, and the displacement for assessing the stiffness. The method of vibration is the rather viable and useful approach for detecting defects in the configuration of the structure, the degradation of the stiffness, and the integrity of the structure under consideration.

This study aims to suggest a strategy for detecting damages of a defected structure, classifying the damages, and predict the quality of material of the structure.

Location of damages

Localized damage could be determined by applying the assumption that the damage can be characterized by location and the change in stiffness. The ratio of the frequency changes,

$$\frac{\delta\omega_i}{\delta\omega_j} = \frac{\delta g_i}{\delta g_j} = h(r) \tag{1}$$

in which $\delta\omega$i and $\delta\omega$j are changes in frequency of two modes i-th and j-th, i.e., mode shapes of cracked and uncracked structure, respectively; r is the position vector; gi, gj, and h are functions of damage locations. Once the theoretically computed ratio $\delta\omega_i/\delta\omega_j$ equals the experimentally measured, the position of the possible damages could be found [1].

Damping in structure

As for damping as an indicator of defects and damages in structure, structural damping can be an effect of hysteretic vibration in the meaning of material damping. When the energy is low or high at a specific frequency, it could be viewed that the damping is heavy or light, respectively. It depends on the kind of damping, the procedure for determining the damping is suggested appropriately [2].

Damping indicates the decrease in amplitudes of responsive displacements. Then by calculating the logarithmic-decrement, normally denoted δ, the severity of damage could be revealed.

$$\delta = \frac{1}{2\pi} Log \frac{A_i}{A_{i-1}} \tag{2}$$

where A_i is the time-domain response amplitude at a specific time t_i. In case δ>0.2, it is predictable there is a severe damage in the structure. An alternative is to analyze the signals in frequency domain to check wheter the magnitude of a response is high or small, or heavily or lightly damping (Figure 1). The higher magnitude in frequency domain, the severity is heavily damped, implying the severe damage in the structure.

The strategy for applying the vibration which concerns the damping would faces mainly four kinds of damping: friction damping (namely Coulomb damping), viscous damping, structural damping, and interracial damping. The last one is due to some contact between interfaces of machine parts that dissipates the energy of vibration.

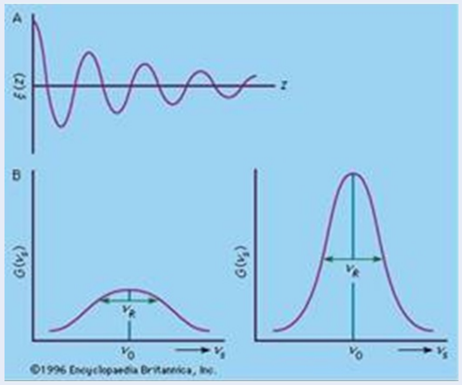

Figure 1: It depends on the response in time domain and in frequency domain, the effect of damping could be analysed (*ource: Encyclopedia Britainnical, Inc*).

Mechanical Impedance

The mechanical impedance or the reciprocation of the mobility, of the structure is defined as below:

$$Z = \frac{EA}{V} \propto \frac{F}{V} \quad (3)$$

in which F is the force applied to the structure in the axial direction. Any changes in E, A, or V due to defects, reduction/enlargement in cross-section, and low quality, etc. would result in a variation in the impedance. The change in impedance would change due to either the decrease in stiffness, the changes in cross-section, or velocity of the longitudinal wave in the structure. With data analysis that is based partly on the maximum and minimum values of the structure mobility (i.e., ratio F/V), the maximum and minimum area of the cross-section are computed [3].

Method uses Transversal Wave Propagation

Once an excitation is applied to the structure, the longitudinal and transversal waves (shear waves) will travel simultaneously within the structure body. This technique is also applicable to inelastic structures such as timber, rip-rap rock, and Jareev (2020) [4], as in Figure 2.

By hearing using geophone for sonic sound, or seismic sensor mounting along the structure shaft, the response will be recorded at both the end of the structure; if there is a defect, the change in velocity amplitude will be found.

Strategy for testing by vibration

The cracked structure is associated with the nonlinear relationship between the cause and the effects. For instance, the relationship between bending moment versus curvature, stress v/s strain with the varied location of the neutral axis, etc. [5]

Uncontrollable factors are encountered, the limit state to be complied with, or N1, and the initial conditions of the restraints to be applied to the structure, N2. The strategy for analyzing the problem is Figure 3.

X1 to X5 are tests applied to structure.

Stage 1: Uncracked structure

The first crack appears when the strain exceeds the limit value, or the principal stress is greater than the tensile strength of the concrete material. The location of the neutral axis will change, resulting in a change in strain in concrete. In this study, according to the ACI [6], the maximum compression strain is limited to ε_{cu}= 0.003 or

$$\varepsilon_c^{'} = 1.71 \frac{f_c^{'}}{E_c} \quad (4)$$

in which, f'_c and E_c are respectively the compression stress and the material stiffness of concrete. In this stage, damage index method (DIM) could be applied to detect the location and severity of damages [7].

Step 1: modal analysis for determining the natural frequency of the structure.

Step 2: Increase the load to P_{cr} and P_{max} with respect to the load of the first crack observed, and of the most sagged beam, respectively.

Step 3: Compare between P_{max} and P_{cr}, compute the damage index (DI) standing for the performance of the structure under bending [8].

$$DI = \frac{P - P_{cr}}{P_{max} - P_{cr}} \quad (5)$$

Or in general formula

$$D.I_{beam} = \frac{X - X_{cr}}{X_{max} - X_{cr}} \quad (6)$$

in which the X_{cr} is the load or dynamic effects or 'causes' at which the crack appears, X_{max} being the load or dynamic effects with which the response exceeds an acceptable value. The effects should be the load causing either the value of bending moment laying between M_{cr} and M_{yield} in Figure 4. [7]

Step 4: Compare DI to criteria [7] to evaluate the structure under static load which relates cracks and the deflection only.

Stage 2: Vibration test

Step 5: Lumped mass of cracked beam (increasing mass, but the stiffness reduced), recalculate the frequencies to determine whether there is a decrease in natural frequencies. Plot the mode shapes. This would be the first criteria for confirming the existence of cracks in the structure.

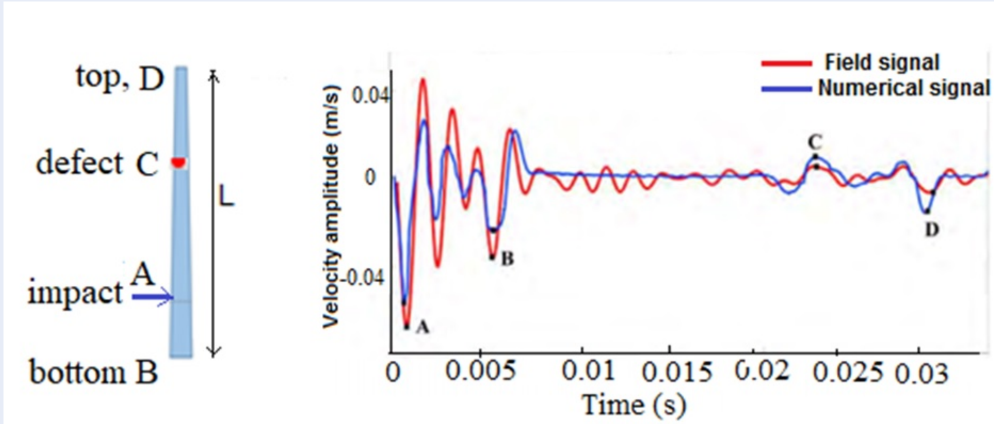

Figure 2: Shear wave propagation method [4].

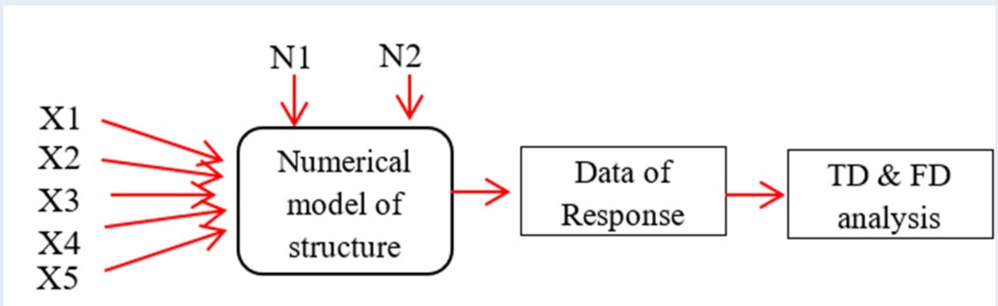

Figure 3: Schematic diagram for collecting the responses

Step 6: Compute the modified flexural damage index (MFDI) [8]

$$MFDI = \frac{1/\omega^2 - 1/\omega_{cr}^2}{1/\omega_{max}^2 - 1/\omega_{cr}^2} \tag{7}$$

Step 7: Applying a dynamic loading with excitation frequency $\bar{\omega}$. The beam becomes a single degree of freedom mass (SdoF) vibrates without damping. If there are unsymmetric cracks, the structure is an eccentric mass, participating in motion with the dynamic loading, then some supplementary frequencies appear in the frequency domain analysis. This could be solved by considering parts of the beam as lumped masses. This analytical can solved efficiently by Matlab Simulink Toolbox, providing that the springs standing for the connection between sections of beam k and km are properly modeled (Figure 5).

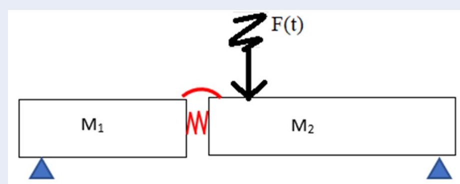

Figure 5: Conceptual lumped mass model in case of unsymmetric cracks in a beam acting as multi-degree of freedom (MdoF) system.

Step 8: Parametric study conducted over the range of material stiffness, i.e., modulus of elasticity E. This step deals with the integrity of the material. Results of responses such as frequencies, acceleration, velocity, and displacement from FD analysis would be compared one-by-one to that of the responses of the uncracked beam in Step 1.

Step 9: In this step, an out-of-bond condition in rebars and reinforced polymers (if any) would be detected. A moving mass MV would be a source of excitation, and an accelerometer transducer A is scanning along the beam during the process of structure vibration. This technique is described in Saleh *et. al.* (2016) [8] with schematic diagram for the test as in Figure 6.

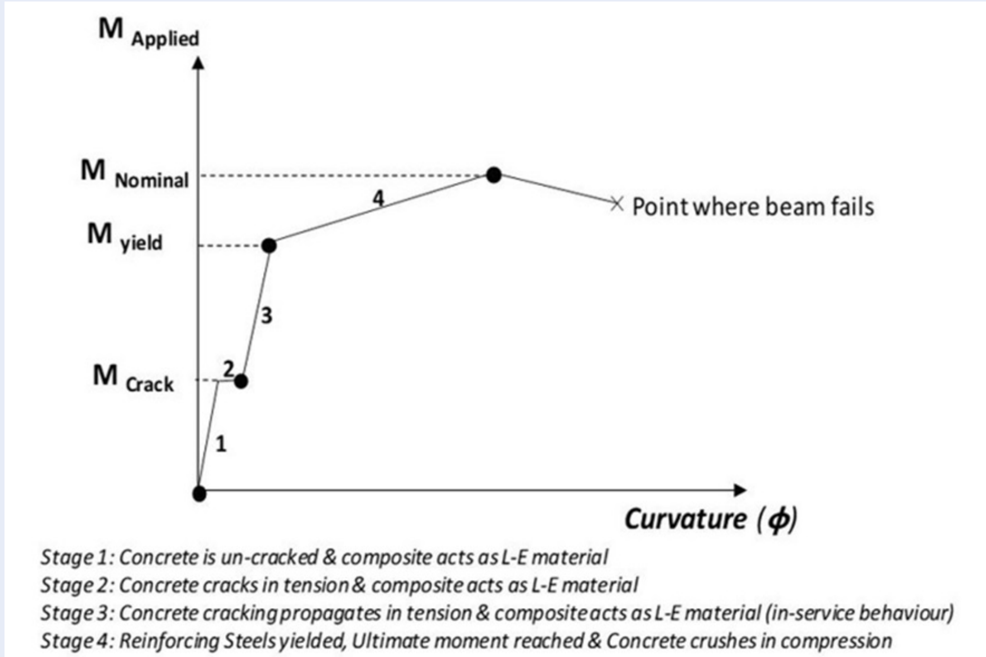

Figure 4: Variuos stages of bending of a beam to failure [7].

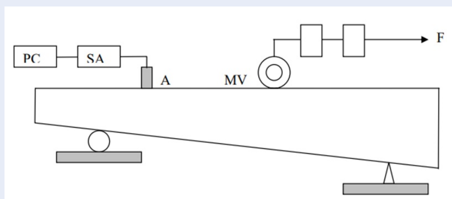

Figure 6: Techniques of using moving acceleration [8].

In the numerical model in this study, the acceleration sensor is replaced by a particle at which, the acceleration is obtained. A moving force F has the amplitude m.r.$\bar{\omega}^2$ acting up and down vertically. For a tentative model, this paper only aims at the investigation of frequency to assess the damages in an RC beam. Dynamic test concerning the MFDI and technique of modeling the beam subjected to moving source of vibration is beyond this paper.

Fast Fourier Transformation

Fast Fourier Transform (FFT) is the traditional way to convert the time-domain signals to the frequency-domain response. This transformation is very important to understand more about the modes of responses. According to this technique, data in time-domain which have ns recordings, and the sampling frequency fs being the total time of sampling divided by ns. Nyquist frequency, f_N, will be the $f_s/2$ (fs=1/T_s). The number of periods n.pf during the time of sampling and the number of samples in a period will be ns/npf. As such, the frequency resolution in frequency domain (FD) analysis requires a sampling frequency f_{res} = 1/T_s. Time-domain (TD) recording requires at least 2n data for being sufficient in FFT. The bigger amount of data is, the more precise the frequency spectrum is. TD and FD analysis clarify the existence of localized damages. By collecting a sufficient database, better supported by some data-driven method, for instance, the Artificial Neural Network method, the problem of diagnosing damages and defects is appropriately solved [9].

MODEL AND PRELIMINARY RESULTS

A specific 6 m-long RC beam is modeled in SAP2000 (Figure 7). According to the American Concrete Institute, or ACI, the cross-sections of the main elements with cracks are normally suggested as shown in Table 1. However, the beam is modeled by Solid 8-node elements, equally divided along the axis of the beam. The damaged zones are modeled as nearly zero stiffness elements. The damages would be either a reduction in cross-section or low-density material (i.e., low value of the elastic modulus E). To come closer to the exact modeling, only a partial element is of very small stiffness, which stands for the zero stiffness of cracked zones. For ensuring the dynamic analysis, the beam subjected to static loading is first examined. Once the beam has proved to be relevant in the response (i.e., deflection and bending moment), then the beam is brought into vibration tests of Stage 2 mentioned above. For simplicity, the results of Stage 1 are checked and displayed as in Figure 7.

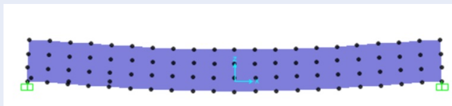

Figure 7: Model of RC uncracked beam with 1% reinforcement converted to equivalent concrete.

The rebar contributes no stiffness to the overall stiffness in calculation the mode shape, this is because based upon the technical viewpoint considering the deflection of the RC beam without taking any percentage of rebar into account, the beam vibrates as a multi-degree of freedom body with uniformly distributed masses. The first four-mode shapes for uncracked structure, low density (i.e., poor quality are plotted in Figure 8.

The frequencies for the first four modes are $f_1 = 26.64$ Hz, $f_2 = 79.18$ Hz, $f_3 = 130.54$ Hz, and $f_4 = 203.92$ Hz for uncracked beam, and $f_1 = 23.36$ Hz, $f_2 = 79$ Hz, $f_3 = 121.16$ Hz, and $f_4 = 202.10$ Hz for cracked beam. When the cracked zone widened, but still symmetrical (see Figure 9), there is a decrease in stiffness, the natural frequencies are tabulated as in Table I. The frequencies seem unchanged when the cracks are symmetrically located, with large numbers of cracks (see bold numbers in Table I). The maximum strain at the lower edge of the beam is nearly 32% in the case of a crack locating in the middle of the structure.

There are three patterns of cracks, classified into 2 groups of damages: symmetrical cracks and unsymmetrical cracks; in the pattern of unsymmetrical cracks, the model examines two scenarios, they are staggered positions and continous positions. Staggered or alternating positions are designed as in Figure 10.

The Table 1 prescribes the frequencies of the free vibration without damping. These results are obtained by SAP2000 analysis [10].

For investigating the responsive frequencies of the beam having the low-density material, the model applies the reduction in the weight per unit volume,

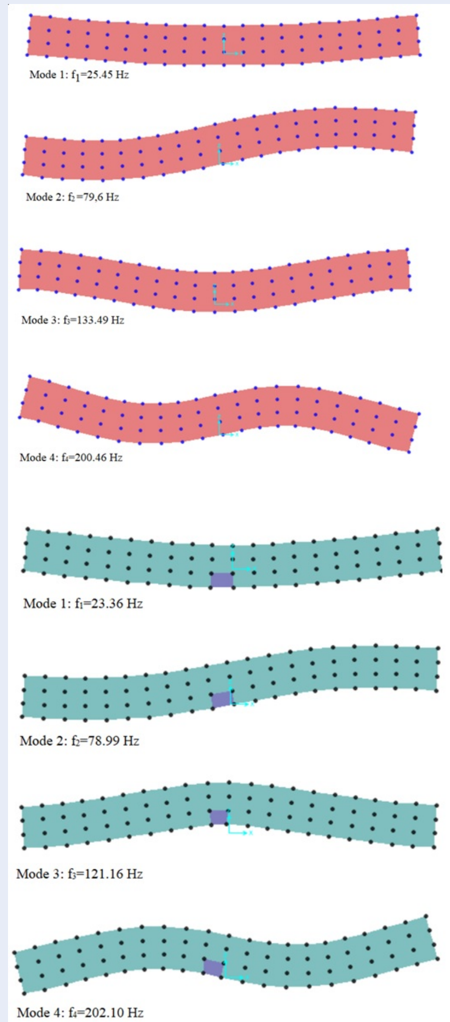

Figure 8: The first four mode shapes of an uncracked beam, uncracked beam (in dark color), and unsymmetric localized crack (violet).

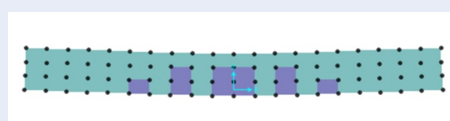

Figure 9: Cracked beam with 3 positions of cracks, f_1=8.04 Hz. Strain vectors of the large deformation widened in the tensile zone of the cracked beam.

Table 1: Natural frequencies of cracked beam (in Hertz)

Characteristics of localized defects	No. cracks zones	f_1	f_2	f_3	f_4
Symmetrical position, alternatively located	2	10.65	35.63	36.34	36.42
	3	17.60	36.03	39.97	46.02
	2*	8.04	35.64	36.34	36.42
	3*	7.14	31.52	35.63	36.34
	4*	7.12	31.52	35.63	36.34
Unsym. position (one-sided cracked region)	2	12.97	76.44	103.27	183.40
	3	9.16	53.67	95.29	134.34
	4	9.14	53.06	94.50	133.82

Note: 2*, 3* and 4* are three scenarios of cracks

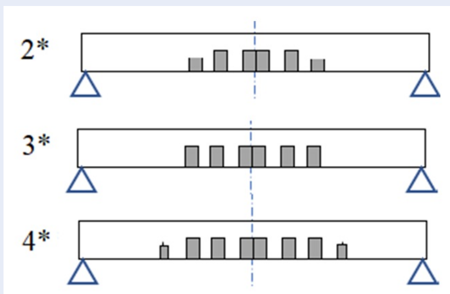

Figure 10: Three scenarios of alternating cracks (shaded rectangulars). Symbols 2* 3* and 4* denote the number of cracks.

light-weight concrete, and a shear strength reduction factor of 0.7. It means that the quality of concrete implies a reduction out of 70% of the shear strength of the material. Properties for such a low-density concrete are reported in Figure 11.

The frequency of a beam made of low-density concrete decreases slightly as compared one by one to that of a beam having good quality material. The frequencies in this case decrease slightly, providing that there is no unsymmetric density in the material.

The responsive frequencies in the low-density scenario decrease from less than 5 % at the dominant frequency to 10.9% at the higher mode of responses (see Table 2).

But for the scenario of partially fixed support, the frequencies decrease slightly at the first and lowest frequency f_1. It is predicted that this result depends on the stiffness of the spring assigned to the model. In real structure, the rigid region of the connection should be studied with an advanced numerical model.

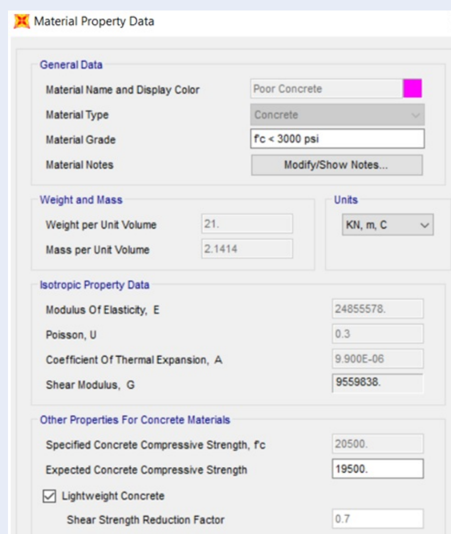

Figure 11: The properties of a low density concrete.

DISCUSSION

This study firstly indicates how the frequency of the structure decreases in terms of different patterns and scenarios of damages. Although some abovementioned preliminary results are clear, there should consider some key points as follows::

1. Since the reinforcement or rebar embedded in the concrete could be converted to the equivalent area of concrete and symmetrically distributed, the results of free vibration of the RC

Table 2: Natural frequencies of low density beam (in Hertz)

Material	f_1	f_2	f_3	f_4
Low E, restraints	26.65	87.13	130.98	225.01
Partially fixed support by spring k=9e4 kN/m	25.45	79.59	133.49	200.46

beam would be acceptable.

2. The flexural capacity of the beam can be easily determined, using the theorem of the textbook Reinforced Concrete Design. Therefore in Stage 1, P_{max} and P_{cr} in the formula (5) are determined. The formulas (5) and (6) are used in assessing the performance of a structure subject to a transversal bending due to vertical static loading, and the (6) for dynamic structures.
3. The variation in the natural frequency of the simply supported beam modeled by SAP2000 is more complicated in the unsymmetric pattens of cracks than that of the symmetric ones. Nevertheless, if the cracks are alternatingly located in one side of the beam, the structure proves to be of higher stiffness at the same numbers of symmetrical patterns of cracks. The mode shapes are different.
4. It is necessary to detect the location of damage. The method of modal strain energy (MSE) could be a viable method. In real practice, the location of damage could be detected by wave propagation method [3,4]. If there is a time-dependent excitation exerted on the structure and stirred it vibrating, then the response in time domain could be analyzed in frequency-domain to detect some dominant frequency and others, then the condition of the structure could be assesed. Besides, damping will be determined quantitatively by investigating the amplitudes of responsive displacements. This is the next step with details followed by this study.
5. Scenarios of cracks which are modeled as 8-node solid element blocks having the nearly zero stiffness has not taken the non-linear relationship between stress and strain, and the widened cracks. This should be overcome by applying some other powerful finite element software such as ANSYS, ABAQUS, etc.

CONCLUSION

Frequency analysis has proved to be a good measure to assess the damaged condition of a structure. There are criteria with which practitioners could use to quantitatively assess the performance of a structure. This study suggests a two-stage strategy of testing, including a test with an uncracked structure for getting data about the damage index and the natural frequency of the structure; then vibration tests could be applied to the structure associated with a variety of scenarios of cracks, to obtain a database of responses. In the framework of this paper, the model developed by SAP2000 is used as a pilot test before conducting it in a scaled model. Results about the decrease in frequency relate closely to the degradation in stiffness and strength, the especially unsymmetric configuration of materials, and positions of cracks. In real practice, such a structure could be tested to evaluate the natural frequency for the first mode of vibration. Results from this study could be further in both theoretical and experimental aspects, especially vibration tests to help technicians and engineers have another tool in technical diagnose.

ABBREVIATION

TD: Time-domain.
FD: Frequency-domain.
DI: Damage Index.
RC: Reinforced Concrete, bê tông cốt thép.
Sdof (Mdof): Single (multi) degree of freedom.
FFT: Fast Fourier Transformation.
MSE: Modal Strain Energy

CONFLICT OF INTEREST

Corresponding author confirms there is no conflict in this article.

AUTHOR'S CONTRIBUTION

Corresponding author implemented all the materials and results described in this article.

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TÓM TẮT

Một kết cấu hư hỏng có độ cứng bị sút giảm do vật liệu, và/hoặc sự giảm yếu tiết diện ngang, và sự giảm cấp về độ bền. Động lực nghiên cứu này là để tìm ra những đặc trưng điển hình trong phổ ứng xử, tần số của kết cấu bị hư hỏng như vậy, trong suốt quá trình chịu tải ngoài. Bằng cách áp dụng một số thử nghiệm cả về mô hình số và thí nghiệm trên mô hình vật lý, vốn cần được thiết kế kỹ càng để cho kết cấu ấy trải qua những điều kiện làm việc tiêu biểu nhất, liên quan đến những yếu tố kiểm soát được và không kiểm soát được, ứng xử của kết cấu được phân tích sâu rộng để hình dung xem những kiểu dáng hư hỏng hoặc phá hoại điển hình nào. Nếu lượng dữ liệu ứng xử trên công trình thực tế được thu thập đầy đủ, theo ý nghĩa các tín hiệu trong miền thời gian và sau đó được phân tích trong miền tần số, thì loại khuyết tật hoặc hư hỏng có thể được xác định.. Kết cấu đang xét trong nghiên cứu này là một dầm đơn giản lương thép 1% được cố ý tạo ra các hư hỏng. Một mô hình số như là thử nghiệm tiên phong được phát triển trước nhất với các kịch bản vết nứt, đối xứng hoặc không đối xứng, chất lượng vật liệu thấp (mật độ thấp). Một chiến lược hai giai đoạn thử tĩnh và thử động được đề xuất. Để bảo đảm điều kiện sát thực nhất có thể, một kiểu liên kết lò xo được gán thay cho gối cố định. Những kết quả chỉ ra rằng sự thay đổi Tần số tự nhiên của dầm tựa đơn giản mô phỏng bằng SAP2000 là phức tạp trong dầm có kiểu thức vết nứt bất đối xứng hơn loại dầm có kiểu thức vết nứt đối xứng, và nếu các vết nứt bố trí xen kẽ, độ cứng vẫn còn cao hơn trường hợp vết nứt sát nhau (liên tục). Ngoài ra, vật liệu mật độ thấp giải thích được sự giảm tần số ứng xử từ khoảng 5 % đến 7,2 % so với tần số của dầm Bê Tông Cốt Thép chất lượng tốt.

Từ khoá: Kết cấu bị hư hỏng, Nguồn kích động rung, Ứng xử tần số, Vật liệu có mật độ thấp, Thử nghiệm đo rung

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