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Damage Identification of Steel Beam Structures Using Dynamic Characteristics

Osman shalan, Atef Eraky Bakry, Rania Samir kamel, Hamedo El Nagdy
Professor of structural analysis, Zagazig University.
Associate Professor, Structural Eng. Dept., Zagazig University.
Ph.D. Student, Structural Eng. Dept., Zagazig University. (Eng.in Suez Canal Authority)

Abstract*—Structural health monitoring has received increasing attention in the civil engineering research community with the objective to identify structural damage at the earliest possible stage and evaluate the remaining useful life of structures. In this research, a non-destructive Vibration-based damage detection method is formulated, and proven to be robust and reliable by investigating its capability to locate and to estimate the severity of damage, based on changes in dynamic characteristics of a structure for identifying structural damage. The residual force method is used to locate the suspected damaged elements and quantify the damage ratios. An extensive parametric study is performed on steel beams with different damage scenarios in order to clarify the validity of the proposed technique using full measurements with consistent mass matrix. Eigen system Realization Algorithm (ERA) is used to extract the structure modal information from the response.

Index Terms—**Damage detection, eigensystem realization algorithm, residual force method.**

I. INTRODUCTION

Non-destructive evaluation and condition assessment of our aging infrastructure have received much attention over the past two decades as a result of the realization that early detection and timely repair of structural damage can enhance the overall safety and prolong the service life of a structure. As proper condition assessment and regular maintenance are vital to the long term health of a structure, there is always the need to develop and implement simple but relatively accurate methods of damage detection that not only capable of evaluating the integrity of the structure, but also perform in a relatively speedy and inexpensive manner. Modal frequencies and mode shapes are the most popular parameters used in the damage identification techniques. The basic idea of these techniques is that the change in modal parameters can easily indicate the presence and severity of damage or faults. The modal frequencies and mode shapes of a structure must satisfy an eigenvalue equation. When potential damage exist in a structure an unbalance error resulting from the substitution of a refined analytical finite element model and the measured modal data into the structure eigenvalue equation will occur, which called the residual modal force. This residual modal force can be used as an indicator of structural damage. To quantitatively identify extent and location of the damage, the residual modal force is further expressed by the element damage index that is the fraction of undamaged element stiffness. Sherman [1] proposed modified residual force vector to detect the structural damage. Baruh and Ratan [2] also used the residual force to detect the damage of beam and truss structure based on undamaged structural analytical mass and stiffness matrices. They used test modal data (natural frequency and mode shapes) to calculate the residual force vector of every mode. They optimized the objective function from residual force by Genetic Algorithm (GA), and obtained good results with noise polluted experimental data. As such, Mares and Surace [3], Rao *et al*. [4] proposed a genetic algorithm to identify damage in elastic structures. The location and the extent of the damage were performed with genetic techniques implemented by using the residual force method, which is based on conventional modal analysis theory. Panigrahi *et al*. used this concept of damage identification in a shear structure [5] and a tapered and nonhomogeneous beam [6, 7]. In these papers, the authors used full mode shape of all modes that were considered in the objective function formulation. Ricles and Kosmatka [8] explained that the residual force method is effective in damage localization using insufficient modal data. They used residual modal force vectors to localize potentially damaged regions then a weighted sensitivity analysis was conducted to assess the extent of damage. Chiang and Lai [9] combined the residual forces method with the method of simulated evolution for damage identification. The damage localization algorithm based on the residual forces method was shown to successfully locate structural damage in the case that the analytical model used for damage identification. The residual forces concept was employed to so call subspace rotation damage identification algorithm by Kahl and Sirkis [10]. The method was applied to identify the damage in beam element using the strain-based data instead of displacement data. It was found that the translational degrees of freedom are coupled to the rotational degrees of freedom in a beam such that the subspace rotation algorithm does not work when the rotational degrees of freedom are condensed out. In this research, the residual force technique is used to detect the damage in beams. The damaged modal data that used are obtained from full scale measurement responses using eigen system realization algorithm (ERA) method. A numerical damage detection method is developed and an extensive

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parametric study is performed on beam in order to clarify the validity of the proposed technique in locating and quantifying the occurred damage in structures accurately. The proposed study utilizes the consistent mass matrix which has two advantages. First it leads to greater accuracy in the results and rapid convergence to the exact result with an increasing number of finite elements. Second with the consistent-mass approach, the potential and kinematic energy quantities are evaluated in a consistent manner, and therefore the computed values of natural frequency relate to the exact values [11].

II. THEORY AND MODELING

The equation of motion of the structure when subjected to dynamic loads is

$$M\ddot{y} + C\dot{y} + ky = 0 \qquad (1)$$

Many system identification approaches have been developed over the years. One of the widely used approaches classified as time domain technique, the Eigen system Realization Algorithm (ERA) [12]. This method is common for system identification applications, owing to its ability to handle multi-input/multi-output systems. Structural damage identification method based on the residual force vector is studied in this paper assuming that the mass matrix is unchanged as damage occurs. Rania [13] developed specific steps to implement the residual force method. The characteristic equation for an n DOFs finite element model of a damaged structure is:

$$\left(K_d + \lambda_{dj} M\right)\phi_{dj} = 0 \qquad (2)$$

Where M is the structure mass matrix, K_d is the stiffness matrix associated with the damaged structural model, λ_{dj} and φ_{dj} are the j^{th} eigenvalue and eigenvector of the damaged structure respectively, which are obtained from the system identification procedure or directly from field using modern instruments like scanning laser vibrometer. The damaged structural stiffness matrix is calculated as follows:

$$K_d = K_u - \Delta K \qquad (3)$$

Where K_u is the undamaged structure stiffness matrix and ΔK is the corresponding changes in the stiffness matrix. Substituting equation (3) into equation (2) yields:

$$\left(K_u - \lambda_{dj} M\right)\phi_{dj} = \Delta K \phi_{dj} \qquad (4)$$

Let $\Delta K . \varphi_{dj} = b_j$, then equation (4) can be rewritten as:

$$b_j = \left(K_u - \lambda_{dj} M\right)\phi_{dj} \qquad (5)$$

Where b_j is the j^{th} residual force vector. A residual force square matrix B is constructed with size (*nxn*) as n is the number of degrees of freedom, where each column in this matrix represents the vector (b_j) as follows:

$$B = \lfloor b_1 \quad b_2 \quad \ldots \quad b_j \quad \ldots \quad b_n \rfloor \qquad (6)$$

The residual force matrix *B* is reshaped to be a single vector with size (*n2 x 1*) which called the reshaped residual force B*.

$$B^* = \lfloor b_1 \quad b_2 \quad \ldots \quad b_j \quad \ldots \quad b_n \rfloor^T \qquad (7)$$

A reshaped damaged modal stiffness matrix (L) with size ($n^2 * n_e$) has to be constructed by reshaping the element modal stiffness matrix for each element where n_e is the number of elements. The relation between the reshaped residual force and the reshaped damaged modal stiffness matrix is:

$$L\alpha = B^* \qquad (8)$$

Where α is the damage ratios vector which contains the damage ratio in each element of the structure (α_i) as follows:

$$\alpha = \lfloor \alpha_1 \quad \alpha_2 \quad \ldots \quad \alpha_{ne} \rfloor \qquad (9)$$

The element damage ratios can be obtained from the previous equation as follows:

$$\alpha = L^+ B^* \qquad (10)$$

Where *L+* is the pseudo-inverse of the matrix L.

A simulated beam shown in Fig (1) is used to verify the proposed study. The beam model is divided into seven elements with twelve translational and rotational DOFs. The properties of the beam model are listed in table (1).

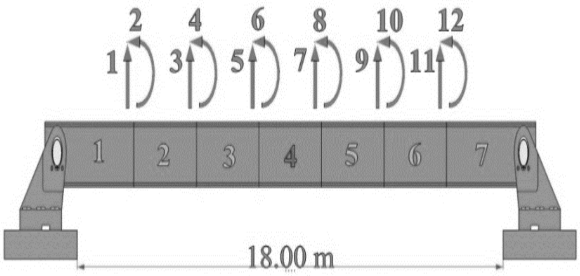

Fig (1) Simple Beam with All DOFs.

Table (1) Elements Properties

Property		value
Area, (A)	[m^2]	1.80E-03
Inertia, (I)	[m^4]	2.46E-06
Mass, (M)	[ton]	1.44E-03
young's Modulus, (E)	[m^2]	2.04E+07

The damage is introduced as a reduction in the young's Modulus (E) of the elements. The element damage ratio is the ratio between the damaged element young's Modulus and the undamaged one. Three levels of damage ratios are studied; 0.1, 0.3 and 0.5 which indicate small, moderate and severe damage respectively. Each damage level is performed with

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three damage scenarios; single damaged element, double damaged elements and damage in all elements. Two strategies will be studied for damage in all elements, the first strategy is assuming equal damage ratios occurred in all members simultaneously, and the second strategy is assuming graded damage ratios from 0.1 to 0.7. The damaged beam is simulated using Matlab program and subjected to impulse force in Z direction at the fifth DOF (U5).

III. RESULTS AND DISCUSSION

A. *Single Damaged Element*

In single damaged element scenario, damage presents in one element only, while the rest elements are healthy. When the fifth element is damaged with ratio equals 10%, and the proposed technique is applied, the predicted damage ratios in all elements are shown in Fig (2). It is demonstrated that the damage ratio in each element is approximately zero except the element number five which has damage ratio coincide with the occurred damage ratio (0.1). The damage detection error, which is calculated as the absolute difference between the detected and the actual damage ratio, is shown in Fig (3). It is found that the error in all elements is very small which indicates accurate damage detection.

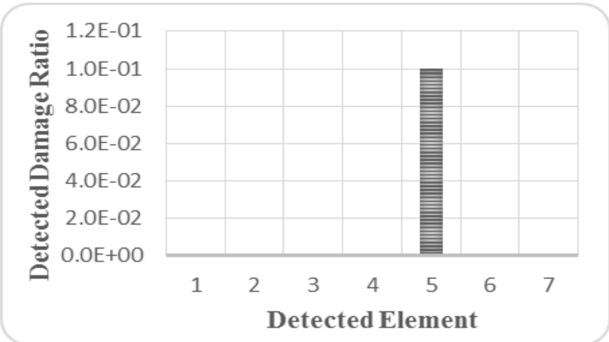

Fig (2): Detected Damage Ratio for 10% Damage in element number five.

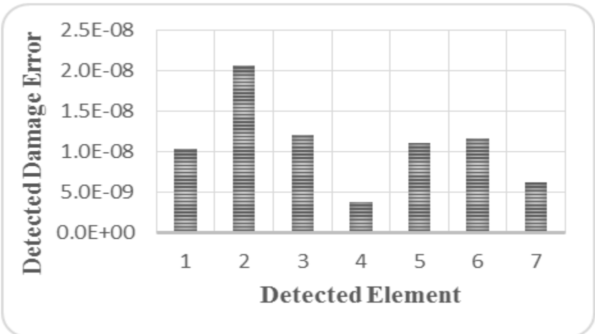

Fig (3) Damage Detection Error for 10% Damage in element number five.

To investigate the validity of the proposed technique, twenty one damage cases are studied for the beam shown in Fig (1). These cases divided into three damage levels; small, moderate and severe damage, each of them occurs in each element individually. Fig (4) indicates the detected damage ratios of all beam elements when single small damage (0.1) is occurred in each element individually. It is found that the detected damage ratios for each case are approximately 0.10 at the damaged element and zeroes at the remaining elements which are the same as the actual damage. It is found that the error of the proposed technique in detecting the damage is very small. Fig (5) shows the damage detection error for each damage case, which indicates that the proposed technique is accurate in detecting the damage ratio in beams when a small damage occurs. The same procedure is repeated for moderate and severe damage (0.3&0.5).The detected damage ratios in all moderate damage cases are shown in Fig (6). The error in detecting damage ratio in each case is shown in Fig (7). When a severe damage is occurred in each element of the beam individually, the proposed technique detects the damage ratio as shown in Fig (8). The error in detecting the damage ratio is very small as shown in Fig (9). It is concluded that the proposed technique is accurate in detecting the damage ratio in beams when a single damage occurs.

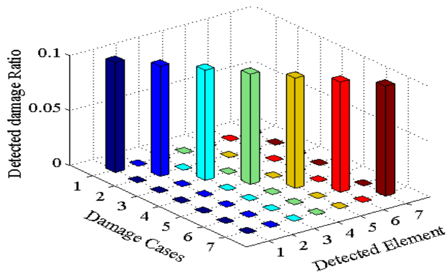

Fig (4) Detected Damage Ratio for Single 10% Damaged elements.

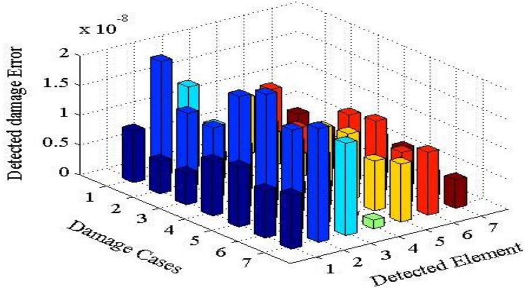

Fig (5) Damage Detection Error for Single 10% Damaged elements.

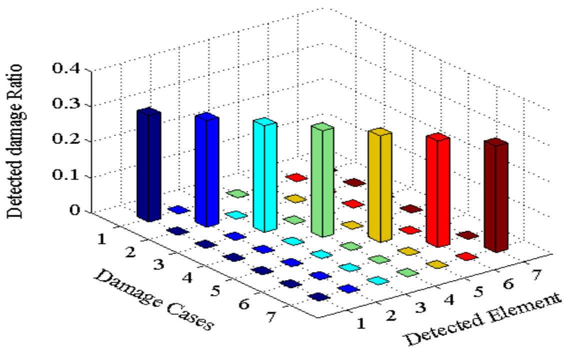

Fig (6) Detected Damage Ratio for Single 30% Damaged elements.

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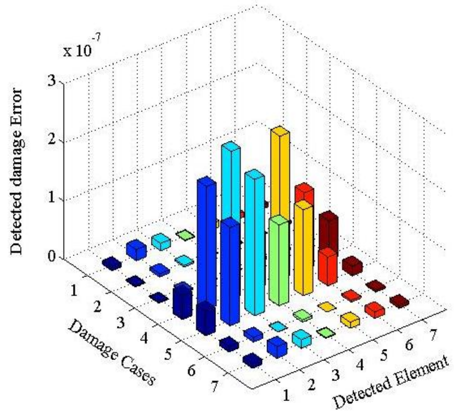

Fig (7) Damage Detection Error for Single 30% Damaged elements.

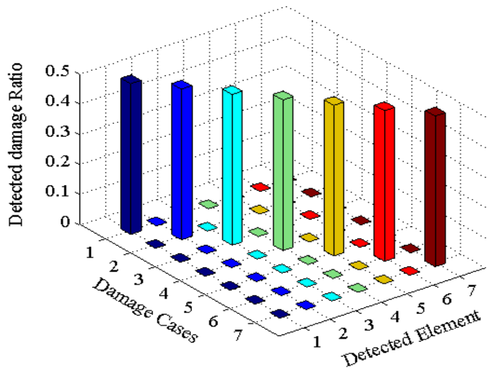

Fig (8) Detected Damage Ratio for Single 50% Damaged elements.

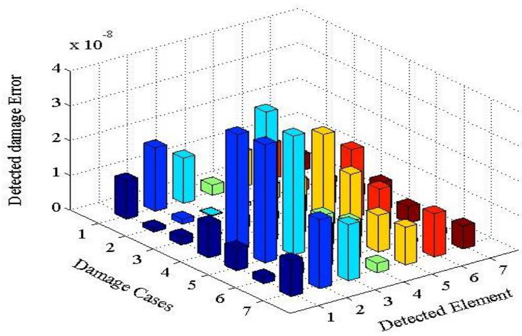

Fig (9) Damage Detection Error for Single 50% Damaged elements.

B. Double damaged elements

When a small damage (0.1) occurs in elements number three and four simultaneously, and the proposed technique is applied; the detected damage ratios and the error in detecting the damage is shown in Fig (10). It is shown that the damage ratios are detected accurately. To investigate the validity of the proposed technique, eighteen damage cases are studied for the beam shown in Fig (1), where the damages occurs in two beam elements. These cases divided into three damage levels; small, moderate and severe damage. Fig (11) indicates the detected damage ratios of all elements in the cases of small damage (0.1) occurred in two beam elements simultaneously. It is found that the detected damage ratios for each case are 0.10 at the damaged elements and approximately zeros at the remaining elements. The error of the proposed technique in detecting the damage ratios is very small as shown in Fig (12). It is found that the maximum damage detection error is very small as it does not exceed 1.93E-08% which indicates that the proposed technique is accurate in detecting the damage ratio in beams when a small double damage occurs. The same procedure performed in the small double damage cases is repeated for moderate and severe damage (0.3 & 0.5) cases. Fig (13) and Fig (14) show the damage detection error in double moderate and severe damage cases respectively. From these figures, it is found that the maximum damage detection error equals to 6.18E-08 % and 3.44E-08 % for moderate and severe damage cases respectively which approve the validity of the proposed technique.

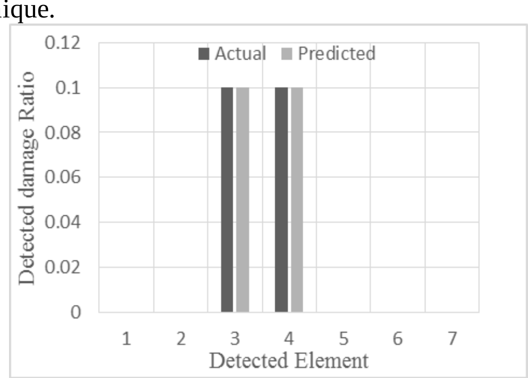

Fig (10) Detected Damage Ratio for double 10% Damaged elements [3, 4].

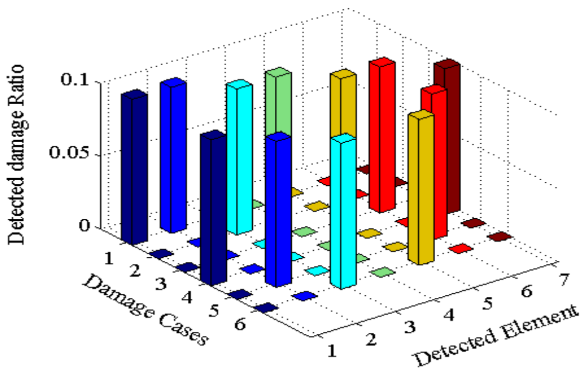

Fig (11) Detected Damage Ratio for double 10% Damaged elements.

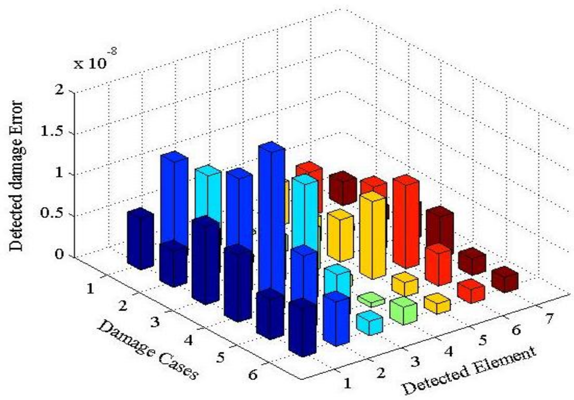

Fig (12) Damage Detection Error for double 10% Damaged elements.

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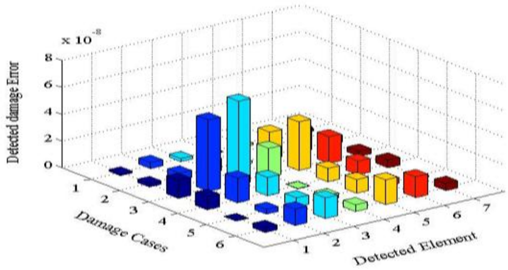

Fig (13) Damage Detection Error for double 30% Damaged elements.

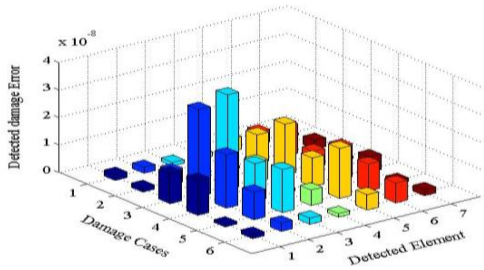

Fig (14) Damage Detection Error for double 50% Damaged elements.

C. Damage in All Elements (Multiple damage)

Four cases of damage in all elements are studied. The first, second and third cases represent equal small, moderate and severe damage in all elements respectively. The fourth case represents graded damage in all elements. The detected damage ratios and the error in detecting the damage in the studied beam are shown in Fig (15) and (16) respectively for the four cases. It is shown that the damage ratios are detected correctly. From Fig (16), it is found that the maximum error in detecting damage equals to 2.47E-08 %, 1.16E-08 %, 1.66E-08 % and 5.54E-09% for small, moderate, severe and graded damage cases respectively. It is obvious that the proposed technique detects the damage in all elements in different cases correctly.

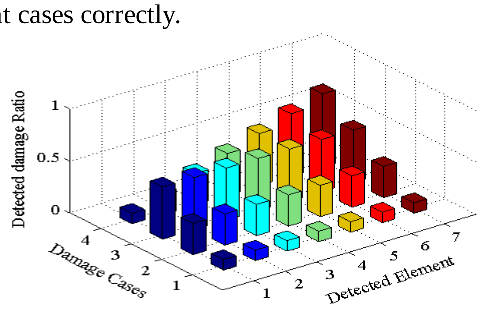

Fig (15) Damage Detection ratio for cases of all damaged elements

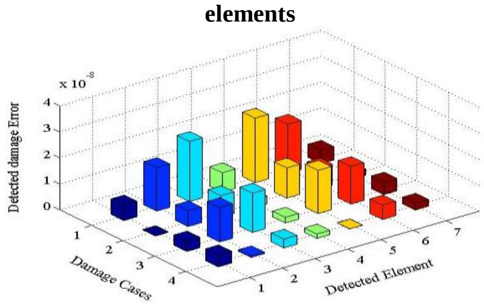

Fig (16) Damage Detection Error for cases of all damaged elements

The maximum errors in detecting damages are summarized in table (3). It can be concluded that maximum error in detecting damage ratio is very small, which means that the proposed damage identification technique is accurate in detecting both the location and severity of damage in simple beam structures.

Table (3) Summary of the maximum detected damage errors (%)

Damaged Case	Damage Ratio	Max. Detected Damage Error %
Single Damaged element	Small	2.07E-08
	Moderate	2.53E-07
	Severe	3.73E-08
Double Damaged elements	Small	1.93E-08
	Moderate	6.18E-08
	Severe	3.44E-08
Damage in all element	Small	2.48E-08
	Moderate	1.16E-08
	Severe	1.66E-08
	Gr’aded	5.54E-09

IV. CONCLUSION

In this research, a non-destructive Vibration-based damage detection method is formulated, and proven to be robust and reliable by investigating its capability to locate and to estimate the severity of damage. The residual force method is used to locate the suspected damaged elements and quantify the damage ratios in a simple beam model. The beam model is divided into seven elements with twelve translational and rotational DOFs. Three levels of damage ratios are studied; 0.1, 0.3 and 0.5 which indicate small, moderate and severe damage respectively. Each damage level is performed with three damage scenarios; single damaged element, double damaged elements and damage in all elements. Graded damage in all elements is also studied. From the research carried out, it can be concluded that the proposed damage identification technique is accurate in detecting both the location and severity of damage in simple beam structures. The proposed damage detection technique can be extended in future to be applied using few measurements data for beams and other types of structures like frames and plates.

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AUTHOR'S PROFILE

Osman shalan Professor of structural analysis, Structural Eng. Dep., Faculty of Engineering, Zagazig University, Egypt. Bachelor of Engineering Construction. Zagazig University, [1985]. Master of Structural Engineering, Zagazig University, [1990]. Doctor of Structural Engineering, Zagazig University, [1995].

Atef Eraky Bakry Professor of structural analysis, Structural Eng. Dep., Faculty of Engineering, Zagazig University, Egypt. Bachelor of Engineering Construction. Zagazig University, [1992]. Master of Structural Engineering, Zagazig University, [1997] (Seismic Base isolation). Doctor of Structural Engineering, Zagazig University, [2000] (Stochastic Structural Base Isolation).

Rania Samir Associate Professor, Structural Eng. Dep., Faculty of Engineering, Zagazig University, Egypt. Bachelor of Civil Engineering. Zagazig University, [2001]. Master of Structural Engineering, Zagazig University, [2005]. Doctor of Structural Engineering, Zagazig University, [2010].

Hamedo El Nagdy Bachelor of Engineering Construction. Assuit University, [2002]. Master of Structural Engineering, Assuit University, [2010] (Structural behavior of R.C Slabs Stiffened with Additional Corner Reinforcement). Ph.D. Student, Structural Eng. Dept., Zagazig University. (Currently Engineer .in Suez Canal Authority).