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DAMAGE DETECTION OF CABLE-STAYED BRIDGES USING CURVATURE CHANGES IN MODAL MODE SHAPES

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ABSTRACT

Presenting SHM “Structural Health Monitoring” techniques that are based on changes in modal characteristics for flexible structures such as cable-stayed bridges is one of the important challenges due to the importance of these structures in the society, taking into consideration the complexity of their dynamic behavior.

In this paper, a proposed damage detection technique based on changes in curvatures of mode shapes is introduced. The results are compared with another two methods, the first based on changes in displacement and the second is the COMAC “Coordinate Modal Assurance Criteria” value using the same procedures of the proposed technique in a verification example of a simple beam using both single and multiple damage scenarios. A proposed computerized analysis tool is introduced to simplify the study.

A case study for The Suez-Canal cable stayed bridge was performed to implement the proposed technique with the proposed analysis tool for both single and multiple damage scenarios.

Keywords: SHM; Damage Identification; MAC; COMAC; Mode Shapes; Displacement; Curvature.

INTRODUCTION

Cable-stayed bridges are considered as one of the long design life, life-safety implications and high capital expenditures structures that are mainly concerned in structural health monitoring researches, which focus on finding out an optimum method for damage detection that based on testing of real structures rather than laboratory tests of those representative structures to quantify and extend their life time. The EMA ‘Experimental Modal Analysis” is one of the best non-destructive techniques that are used for testing and health monitoring of bridges. [1, 2, 3]

The damage detection techniques that based on changing in modal characteristics are classified into two main categories, the first is based on the natural frequency changes and the second is based on the mode shapes changes.

For the first category, the most common method is the forward method in which, a database is created for some assumed damage scenarios for some/all members of the studied structure that contains records for the damage values against the frequency changes for the different mode shapes using any analytical method. The extracted modal frequencies from any EMA test for the studied structure are compared and simulated with those figures of the created database to define the damage location and its value. It is just elimination operation for the supposed damage within the most probable damage scenarios included in the created database that have the same frequency shifts for the different mode shapes. It means that this method validity is depending on the accuracy and efficiency of the presumed damage scenarios that should cover and include the most probable damages, in addition to the frequency shift values of the different damage scenarios that should be clear and relatively large to be measured in nature for the studied structure within the limitations of the measuring tools. Most of the SHM researches had just evaluated and verified this method for simple beams and cantilevers in labs taking into consideration that the measured frequency shifts are so small for the different damage scenarios. **[4, 5, 6]**

Cable-stayed bridges are one of the highly statically indeterminate structures that make this method inappropriate due to the need of presuming hundreds of damage scenarios with a huge database and certainly most of them have similar frequency small shifts that are hardly measured in nature. In addition many damages that may happen are local phenomena of some members that need higher modes with higher frequency values to be detected, which is hardly extracted and identified in any EMA test for such structures like cable-stayed bridges. So the frequency measurements are useful only as an indicator for damages existence.

For the second category, three numerical techniques may be used to identify the damage with a better accuracy. Four methods may be used in this category as follow:

MAC AND COMAC METHOD

This technique uses the modal assurance criteria "MAC" and the coordinate modal assurance criteria "COMAC" that are described by equations (1) and (2). **[7]**

$$MAC\left(\{F_i^x\},\{F_j^y\}\right)=\frac{\left(\{F_i^x\}^T\{F_j^y\}\right)^2}{\left(\{F_i^x\}^T\{F_i^x\}\right)\left(\{F_j^y\}^T\{F_j^y\}\right)} \qquad (1)$$

$$COMAC\left(x,y,q\right)=\frac{\left(\sum_{i=1}^{N}\left(F_{iq}^x\right)\left(F_{iq}^y\right)\right)^2}{\left(\sum_{i=1}^{N}\left(F_{iq}^x\right)^2\right)\left(\sum_{i=1}^{N}\left(F_{iq}^y\right)^2\right)} \qquad (2)$$

Where :

$\{F_i^x\}$ = *mode shape vector of mode i for the structure at status x*

$\{F_j^y\}$ = *mode shape vector of mode j for the structure at status y*

F_{iq}^x = *ordinate of mode i at location q for the structure at status x*

F_{iq}^y = *ordinate of mode i at location q for the structure at status y*

N = *Number of selected modes*

The modal assurance criteria "MAC" measure the degree of correlation between two similar mode shapes ordinates for the all nodes of the structure in two statuses (the intact or undamaged and the damaged statuses) and it varies between "0" value (totally different) and "1" value (totally compatible). Since any mode shape is a function of the structure stiffness, then any change may happen to it, is definitely indicating a change in the structure stiffness due to damage existence and consequently the greater the change the greater the damage value, so the smaller MAC value the greater the damage, therefore MAC value could be used to indicate the damage severity.

The coordinate modal assurance criteria "COMAC" measure the degree of correlation between multiple mode shapes ordinates for a certain node in the structure in two statuses (the intact or undamaged and the damaged statuses) and it varies between "0" value (totally different) and "1" value (totally compatible). Since the change in mode shape happen due to changes in nodes ordinates, which happen due to changes in nodes stiffnesses, then the change in a such node stiffness due a damage in one or more connected members, is represented by changes in the node ordinates of the different mode shapes, so for a such node, the repetition of changes with a considerable value in the different mode shapes may indicates a damage at this node. The smaller the COMAC value the most probable damage location.

DISPLACEMENT CHANGES METHOD

This technique demonstrates the graphical or the numerical presentation of the absolute changes in the modal displacements for the different mode shapes.

CURVATURE CHANGES METHOD

This technique demonstrates that the absolute changes in mode shape curvature can be a very good indicator of damage location that is computed using the modal displacements. [8]

Using the first principals, the beam curvature is presented using equation (3).

$$k = \frac{1}{\rho} = \frac{v''}{\left[1+(v')^2\right]^{\frac{3}{2}}} \tag{3}$$

where: ***v'*** and ***v''*** are the first and the second derivatives of the displacement function respectively.

It is obvious that the assumption of small slopes is equivalent to disregarding $\boldsymbol{(v')^2}$, thus making the denominator in equation (1) equal to one, So the following simplified expression is used for computing curvature of beam undergoing only very small rotation when loaded.

$$k = \frac{1}{\rho} = v'' \tag{4}$$

Where ***v =f(x)*** is the function that represents the displacement shape. The use of a lower degree curve fitting function, for example a third- to fifth-degree polynomial, may tend to flatten out some of the local peaks in the curve and hence may underestimate the corresponding curvature. Therefore, a minimum sixth-degree polynomial function is suggested in order to capture the localized larger curvature. [9]

By using the central difference approximation formula for any function expanded using Taylor series v'' could be obtained as following:

$$k = v'' = \frac{\varphi_{i-1} - 2\varphi_i + \varphi_{i+1}}{h^2} \tag{5}$$

Where h is the grid length of the measuring grid (or the element size of the finite element in a numerical solution) and ϕ_i is the mode shape displacement at the cross-section considered and consequently the curvature mode shape can be obtained from displacement mode shape.

The damage location could be located by calculating the change in curvature for the different nodes of the FEM model between the intact and the damaged cases, where the biggest change indicates the existence of the damage.

STIFFNESS MATRIX UPDATE METHOD

In which the stiffness matrix could be updated directly using a special software, that makes it one of the most accurate technique for damage detection of structures especially for multiple damage scenarios, where it is able to detect the damage location and severity accurately, [10, 11, 12, 13]

The Proposed Technique

First of all the mode shapes ordinates should be normalized or rescaled, where the computed modal displacements of any mode shape are just representing the relative (Not the absolute) displacement for the different structure nodes, so they should be normalized or rescaled using a constant figure, which is the mass that is considered to be the same for both the intact and the damaged structure. Mass-normalized mode shapes are obtained by scaling the mode shapes to satisfy the following equation: [14]

$$[\Phi]^{T} [M] [\Phi] = [I] \qquad (6)$$

Where: [Φ] is the mode shape matrix of the identified modes, [M] is the mass matrix and [I] is the identity matrix. It means that the modal displacements should be multiplied by some factors (called modal participation factors) to achieve the condition represented by equation (6). Those factors are presented as following:

$$f_{xn} = \varphi_n^{T}\ m_x \qquad f_{yn} = \varphi_n^{T}\ m_y \qquad f_{zn} = \varphi_n^{T}\ m_z \qquad (7)$$

Where, φ_n is the mode shape and $\boldsymbol{m_x}$, $\boldsymbol{m_y}$, and, $\boldsymbol{m_z}$ are the unit Acceleration Loads. These factors are the generalized loads acting on the mode due to each of the Acceleration Loads. [15]

Those calculated factors for any mode provides a measure of how important the mode is for computing the response to the Acceleration Loads in each of the three global directions. Also it was found that mode shapes normalization with respect to the natural frequencies is an important issue for any comparison between the intact and the damaged structure. [16]

So to study the modal displacement of the different mode shapes for both the intact and the damaged structure for the different cases, they were multiplied by the modal participation factors and divided by the modal frequencies. The modal participation factors were used to indicate the selected modes taking into consideration that results are affected by particular modes pairs that can indicate the damage, but when all mode pairs are used, the indication of damage is masked by modes that are not sensitive to the damage. [17, 18]

The product of the absolute change (either for curvature or displacement) of the different selected modes is a very good indicator for damage location. [19]

An automated tool was created using Microsoft Excel to simplify the case study for the different cases by the different techniques by giving the ability of changing the applied technique and the selected modes by just entering codes in two fields and consequently the output graphs follow the selection criteria. All calculations equations were predefined following the applied techniques.

The SAP2000 output modal displacements in the vertical direction of the ten modes were imported to the Excel file and normalized with respect to the mass (multiplied by modal participation factors) and the frequencies (divided by the natural frequencies). Figure (1) shows the flow chart of the proposed analysis tool.

VERIFICATION EXAMPLE

A simply supported reinforced concrete beam is used to demonstrate the different techniques of damage detection based on changes in mode shapes. The beam has a cross section of 25cm breadth and 20 cm depth and it is equally divided into 15 two-dimensional beam elements, as shown in fig (2). The concrete material has a modulus of elasticity $\boldsymbol{E}$ =3200000 t/m^2 and unit density

γ =2.5 t/m^3. Multiple damage scenarios were assumed as shown in table (1) and were simulated by reducing the stiffness of the assumed elements. The modal characteristics for the intact (undamaged) case and the damaged cases were calculated using the SAP2000 program.

The simple beam was modeled using two methods to study the effect of modeling technique on results. In the first the beam was modeled by using frame elements and the damage was presented by reduction in the element stiffness (area and inertia). In the second method the beam was modeled using shell elements and the damage was presented by a crack in the bottom of the beam (elements separation).

The first ten modes were extracted for the undamaged case and the different damage cases that are shown in table (1) for the both modeling techniques. The studied nodes are 1 to 16 for both cases that represent the centerline of the beam.

ANALYSIS RESULTS

Table (2) shows the modal participation factors, table (3) shows the modal frequencies and table (4) shows the MAC values of the different scenarios for the both modeling techniques.

Table (1): Damage scenarios for the two modeling techniques

Model Type	Damage Scenario	Damage Type	Damage Location	Damage Severity	Damage Modeling
Frame Elements Model	BD1	Single	Element 8	20%	Stiffness Reduction
	BD2	Single	Element 8	40%	
	BD3	Single	Element 8	50%	
	BD4	Single	Element 8	60%	
	BD5	Single	Element 8	80%	
	BD6	Single	Element 12	50%	
	BD7	Double	Elements 8, 12	50%	
Shell Elements Model	SD1	Single	Node 9	0.5 h	Crack 1cm at bottom
	SD2	Single	Node 13	0.5 h	and zero at CL at
	SD3	Double	Node 9, 13	0.5 h	the middle of height

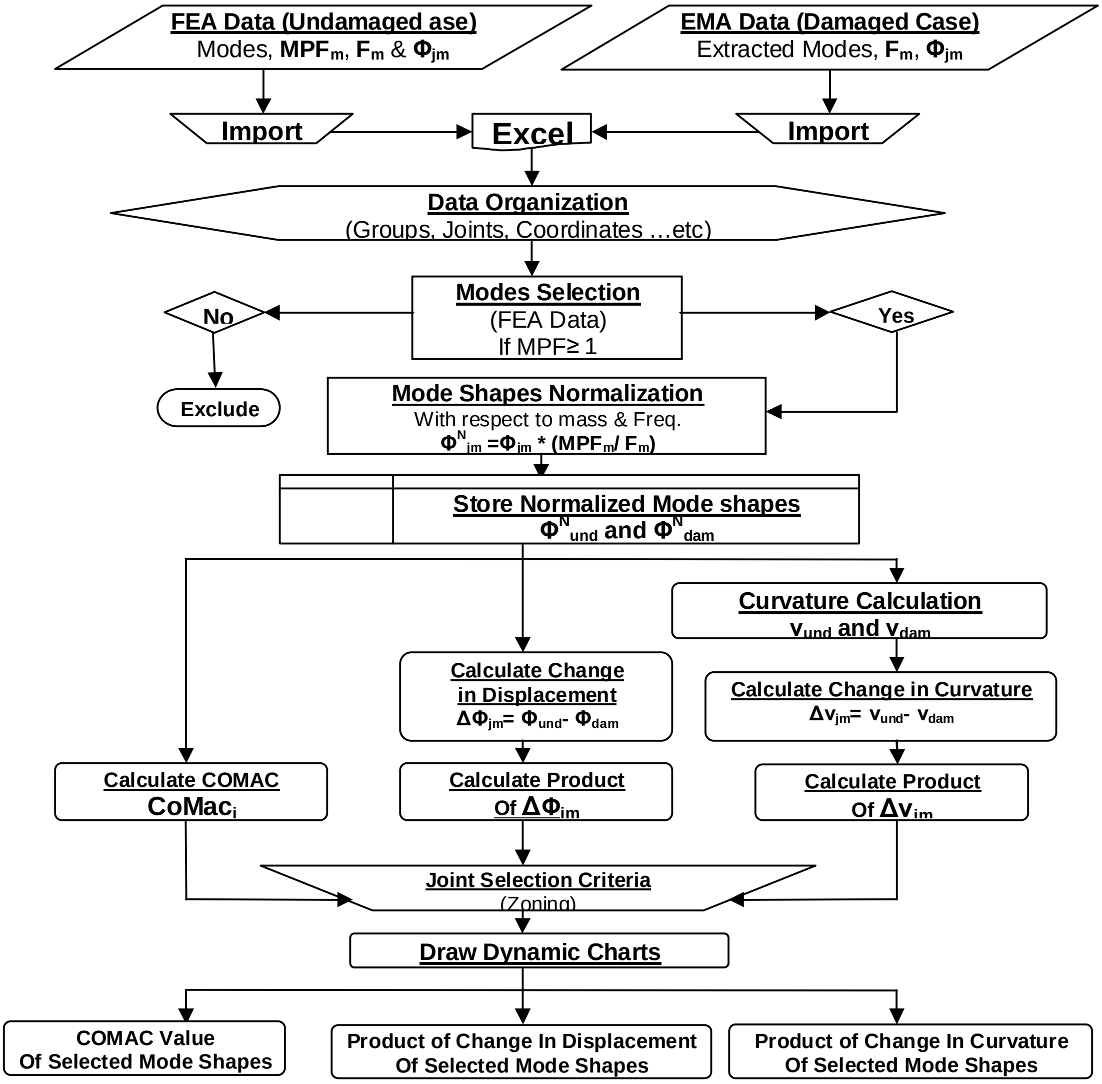


Fig (1): The flow chart of the proposed analysis tool

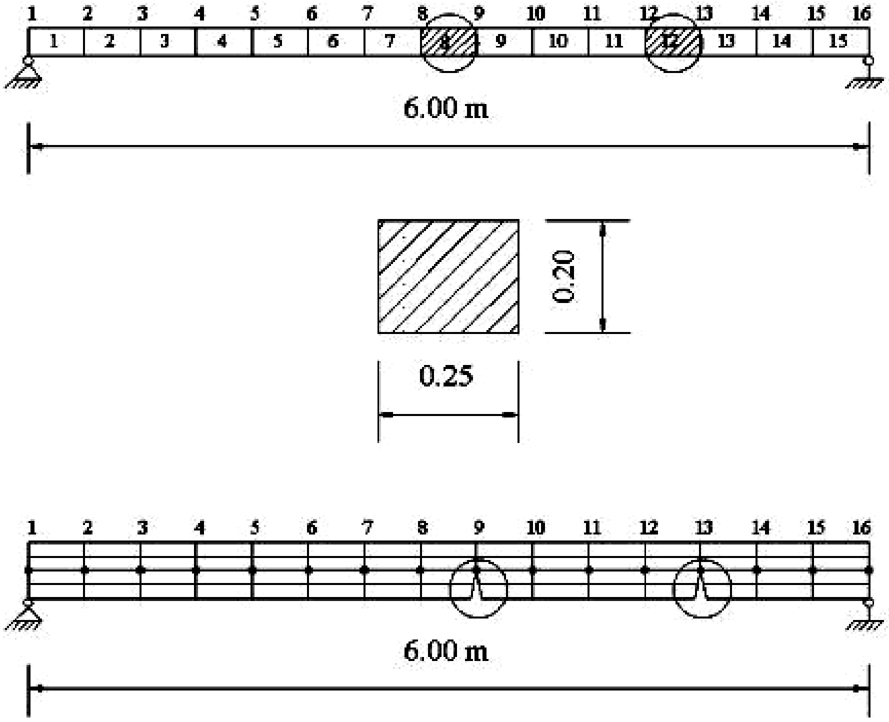


Fig (2): The simulated simply supported beam

Table (2): Modal Participation Factors

M.	Mode	1	2	3	4	5	6	7	8	9	10
Frames Model	Int.	0.248	-8E-16	0.0802	2E-14	-0.0452	2E-13	0.029	3E-12	0.0189	-1E-11
	D1	-0.2478	5E-16	-0.0807	3E-14	0.0454	7E-14	-0.0292	-2E-12	-0.0191	-8E-12
	D2	-0.2474	-1E-15	0.0814	-2E-14	-0.0458	2E-13	0.0295	2E-12	-0.0194	1E-11
	D3	0.2471	2E-15	0.082	-1E-14	-0.0461	9E-13	-0.0297	3E-12	0.0195	5E-12
	D4	-0.2467	4E-16	0.0828	2E-14	-0.0465	-1E-13	0.03	4E-12	-0.0197	5E-12
	D5	0.2452	4E-16	-0.0861	-7E-14	-0.0479	-8E-14	0.0307	-3E-12	0.0201	-3E-11
	D6	0.2484	0.0023	-0.0776	0.0017	-0.0469	-0.001	-0.0292	0.0002	0.0186	0.0017
	D7	-0.2476	-0.001	0.0794	0.0015	0.0477	0.0019	-0.03	8E-05	-0.0191	0.0027
Shells Model	Int.	-0.2479	1E-12	-0.0799	-4E-11	3E-11	-0.0446	-8E-11	-6E-09	-0.0282	5E-09
	D1	-0.247	0.0025	0.0813	-0.0073	1E-05	-0.0451	-0.005	-0.0193	-0.0209	0.0052
	D2	0.2484	0.0006	0.0765	0.0112	0.0001	-0.0446	-0.0058	0.0228	-0.0188	0.0037
	D3	-0.2474	8E-05	0.0784	0.007	0.0085	-0.046	-0.0004	0.0284	-0.0106	-0.0066

Many modes selection trials were done with their corresponding analysis following figures of frequency shifts, MAC values and modal participation factors (M.P.F.). Assuming that the most affected modes are those of the bigger frequency shifts, lower MAC values and the bigger M.P.F. (each case individually). It was found that the best results reached by following M.P.F. figures, so modes 1, 3 and 5 were selected because they have the biggest M.P.F. values. Figs (4) to (15) show the final results with the three proposed analysis techniques for the whole ten modes and for the selected modes (1, 3 and 5) for both modeling techniques, taking into consideration that the damage location is indicated by the lowest COMAC value and the highest value of product of absolute changes in both displacement and curvature.

Table (3): Modal frequencies

Model	Status	Mode	1	2	3	4	5	6	7	8	9	10
	Intact	Freq.	8.9	35.5	79.4	139.7	215.3	304.6	405.2	514.2	627.6	740.4
Frame Elements Model	D1	Freq.	8.8	35.5	78.2	139.5	212.5	303.4	401.1	510.6	623.2	732.4
		Shift%	-1.6%	0.0%	-1.5%	-0.2%	-1.3%	-0.4%	-1.0%	-0.7%	-0.7%	-1.1%
	D2	Freq.	8.5	35.5	76.4	139.1	208.7	301.4	395.7	504.4	617.8	719.0
		Shift%	-4.1%	-0.1%	-3.7%	-0.5%	-3.1%	-1.1%	-2.3%	-1.9%	-1.6%	-2.9%
	D3	Freq.	8.4	35.5	75.2	138.7	206.2	299.7	392.4	499.4	614.7	708.5
		Shift%	-6.0%	-0.2%	-5.2%	-0.7%	-4.2%	-1.6%	-3.2%	-2.9%	-2.1%	-4.3%
	D4	Freq.	8.1	35.4	73.7	138.3	203.2	297.3	388.6	491.7	611.2	694.1
		Shift%	-8.7%	-0.3%	-7.2%	-1.0%	-5.6%	-2.4%	-4.1%	-4.4%	-2.6%	-6.3%
	D5	Freq.	7.2	35.3	68.5	135.8	194.5	284.4	378.9	457.0	602.9	648.0
		Shift%	-19.2%	-0.7%	-13.7%	-2.8%	-9.7%	-6.6%	-6.5%	-11.1%	-3.9%	-12.5%
	D6	Freq.	8.7	33.5	76.7	138.5	211.0	293.6	393.4	499.5	606.7	725.4
		Shift%	-2.9%	-5.6%	-3.4%	-0.8%	-2.0%	-3.6%	-2.9%	-2.9%	-3.3%	-2.0%
	D7	Freq.	8.2	33.4	72.5	137.6	202.7	289.1	380.7	486.3	593.2	693.6
		Shift%	-8.4%	-5.8%	-8.6%	-1.5%	-5.9%	-5.1%	-6.1%	-5.4%	-5.5%	-6.3%
Shell Elements Model	Intact	Freq.	8.9	35.7	80.5	143.2	143.3	224.2	323.7	428.4	441.9	579.3
	D1	Freq.	8.4	35.6	76.3	138.5	143.2	214.7	316.5	415.3	433.6	556.0
		Shift%	-5.7%	-0.3%	-5.2%	-3.3%	0.0%	-4.3%	-2.2%	-3.1%	-1.9%	-4.0%
	D2	Freq.	8.7	33.7	76.1	133.0	143.2	224.2	315.1	402.4	432.5	550.1
		Shift%	-2.3%	-5.7%	-5.4%	-7.2%	-0.1%	0.0%	-2.7%	-6.1%	-2.1%	-5.0%
	D3	Freq.	8.3	33.7	70.7	132.2	139.7	214.4	307.6	398.8	415.7	542.7
		Shift%	-6.8%	-5.7%	-12.2%	-7.7%	-2.5%	-4.4%	-5.0%	-6.9%	-5.9%	-6.3%

Table (4): MAC values of the different damage scenarios

M.	Mode	1	2	3	4	5	6	7	8	9	10
Frames Model	D1	1.0000	1.0000	0.9998	1.0000	0.9995	0.9998	0.9993	0.9990	0.9993	0.9957
	D2	0.9999	1.0000	0.9989	0.9999	0.9972	0.9986	0.9961	0.9926	0.9964	0.9716
	D3	0.9998	1.0000	0.9978	0.9997	0.9947	0.9969	0.9930	0.9835	0.9937	0.9417
	D4	0.9996	1.0000	0.9959	0.9993	0.9906	0.9930	0.9882	0.9642	0.9898	0.8891
	D5	0.9983	0.9999	0.9863	0.9949	0.9728	0.9529	0.9701	0.8306	0.9766	0.6684
	D6	0.9994	0.9969	0.9966	0.9993	0.9940	0.9846	0.9823	0.9705	0.9536	0.9706
	D7	0.9996	0.9964	0.9934	0.9990	0.9919	0.9832	0.9777	0.9682	0.9431	0.9086
Shells M.	D1	0.9998	0.9998	0.9956	0.9518	0.6853	0.9842	0.9784	0.5701	0.9886	0.9346
	D2	0.9995	0.9952	0.9913	0.9264	0.6854	1.0000	0.9720	0.4486	0.9898	0.9270
	D3	0.9996	0.9947	0.9821	0.8946	0.7027	0.9806	0.9728	0.4734	0.7766	0.9085

A commercial program called LAB FIT was used to get the 6th degree polynomial equations that fit the displacements mode shapes for the different scenarios to be used for curvatures calculations using equation (3). The curvatures were calculated also using equation (5) and it was found that the results are approximately identical to those calculated by equation (3). Fig (3) shows a plot for the MAC values versus the damage severity (of the element ‘8’ - frame elements model) for the first mode and damage scenarios D1, D2, D4 and D5 records. The LAB FIT program was used to find out equation that fit the data. Equation (8) is the best fitting function (Beta function), where ***Y*** is the damage severity and ***X*** is the MAC value.

$$Y = (974.852) * (X)^{(175.324)} * (1 - X)^{(0.345)} \qquad (8)$$

By substituting of MAC value of the 1st mode of damage scenario D3 in equation (8), the resultant severity value is (49.2%), which is approximately (50%). So it is valid to use this function to find out the damage severity with a good accuracy.

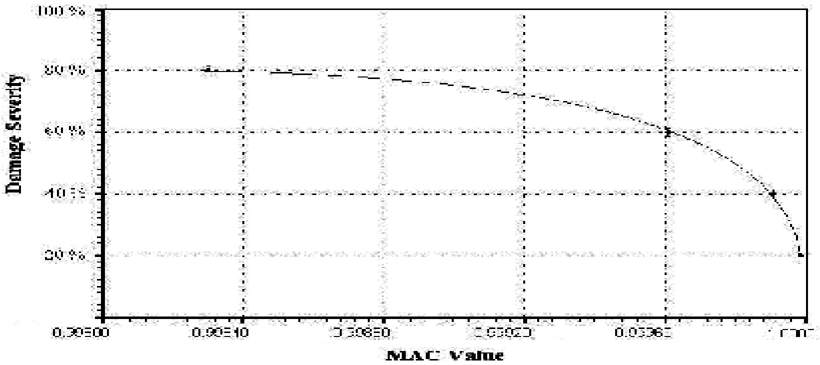


Fig (3): MAC- Damage severity relationship
1st Mode – Frame elements

MODEL RESULTS EVALUATION

By studying the results, it was found that:

- Using all available modes most probably masks the indication of damage because of the modes that are not sensitive to the damage.
- MPFs are a very good guide to the effective modes that should be selected for damage detection analysis.
- COMAC function is inappropriate method for locating the damage especially for the multiple damage scenarios but it could be used to differentiate between two or three locations that calculated by another accurate method.
- The product of the absolute displacements changes method is more effective for single damage scenarios especially with the sensitive modes selection.
- The product of the absolute curvatures changes method is certainly a very powerful method for locating the damage even for the multiple damage scenarios regardless the modes selection.
- Plotting a curve of MAC values versus the damage severity is a good tool to calculate the damage severity for an unknown damage.
- Damage modeling using shell elements (crack at a certain node) is more sensitive and gives better and specific results than stiffness reduction method (frame elements), which reflect the damage on the two nodes of the member and each of them may be connected to more than on member, where in this case reduction in a member stiffness indicates damage in two nodes with three members.

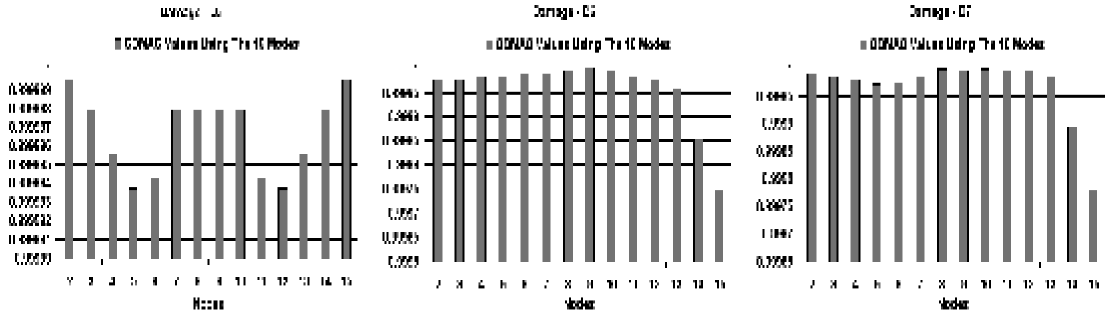


Fig (4): COMAC values using the 10 modes
For the different Damage scenarios – Frame elements model

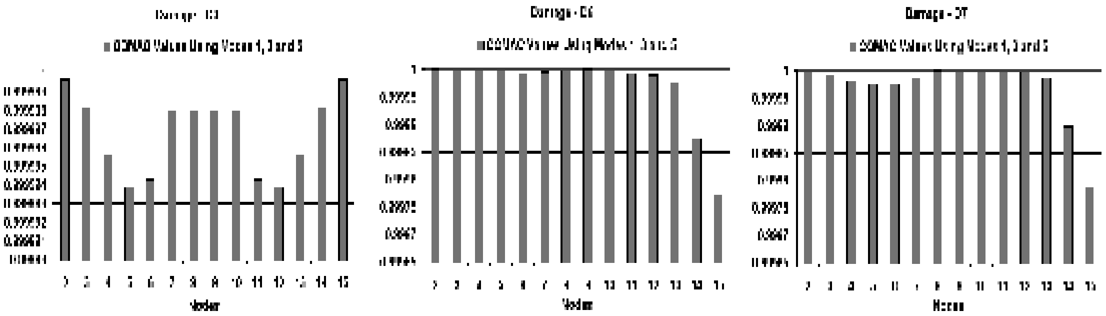


Fig (5): COMAC values using modes 1,3 and 5
For the different Damage scenarios – Frame elements model

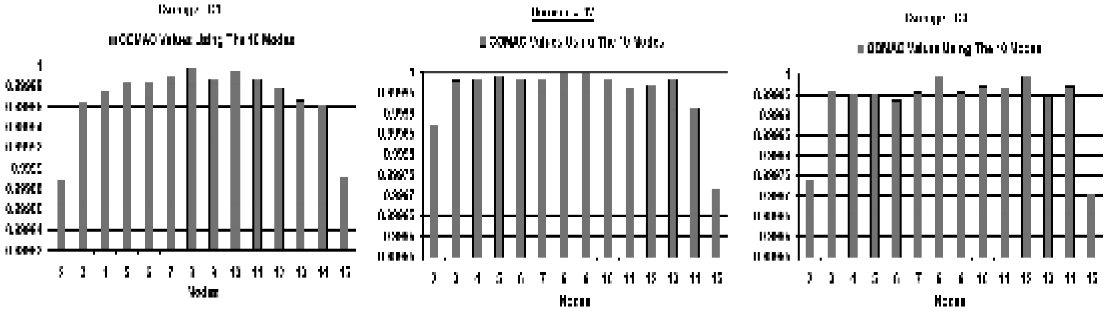


Fig (6): COMAC values using the 10 modes
For the different Damage scenarios – Shell elements model

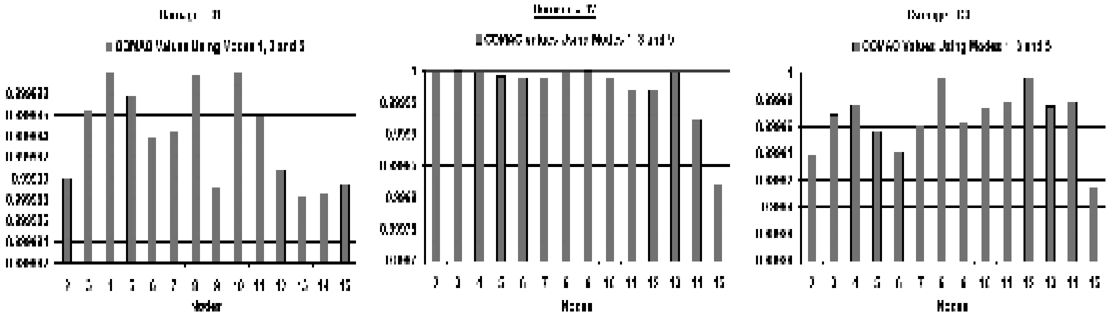


Fig (7): COMAC values using modes 1,3 and 5
For the different Damage scenarios – Shell elements model

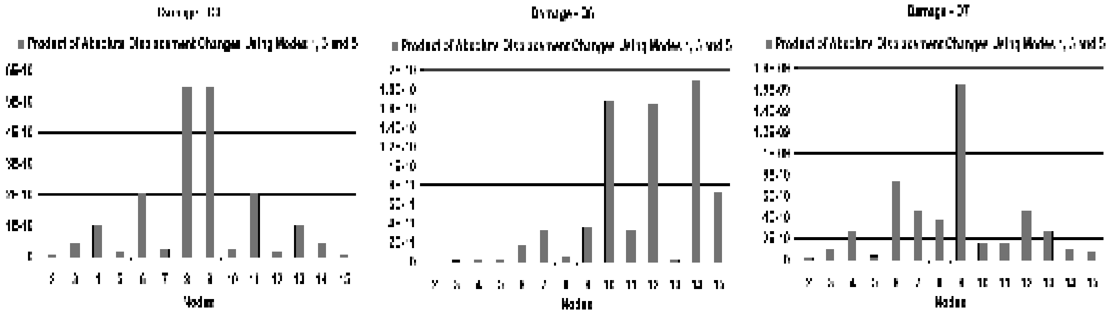


Fig (8): Product of ADC using 10 modes
For the different Damage scenarios – Frame elements model

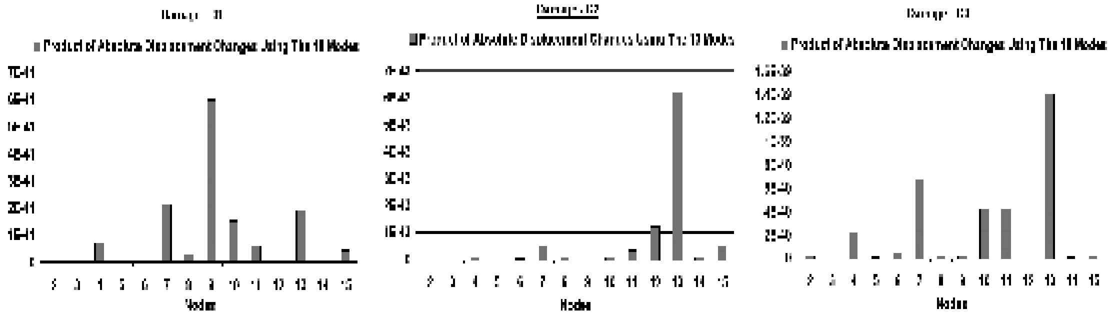


Fig (9): Product of ADC using modes 1,3 and 5
For the different Damage scenarios – Frame elements model

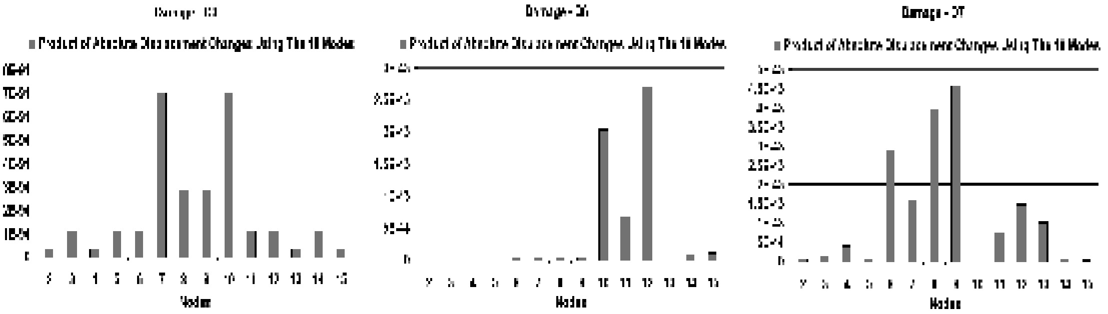


Fig (10): Product of ADC using 10 modes
For the different Damage scenarios – Shell elements model

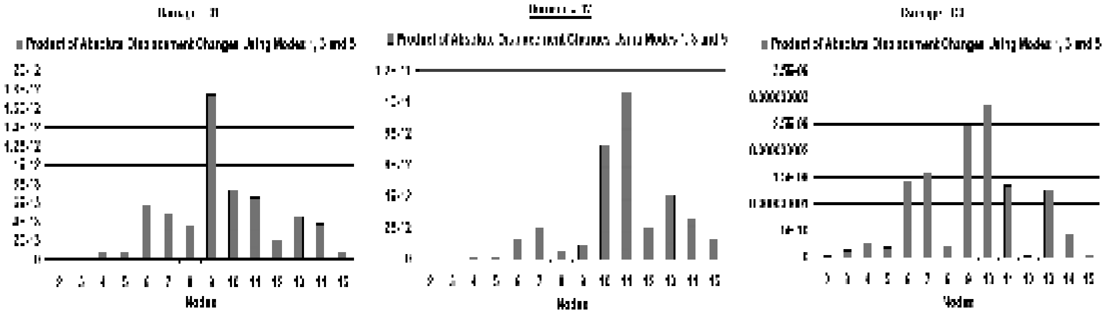
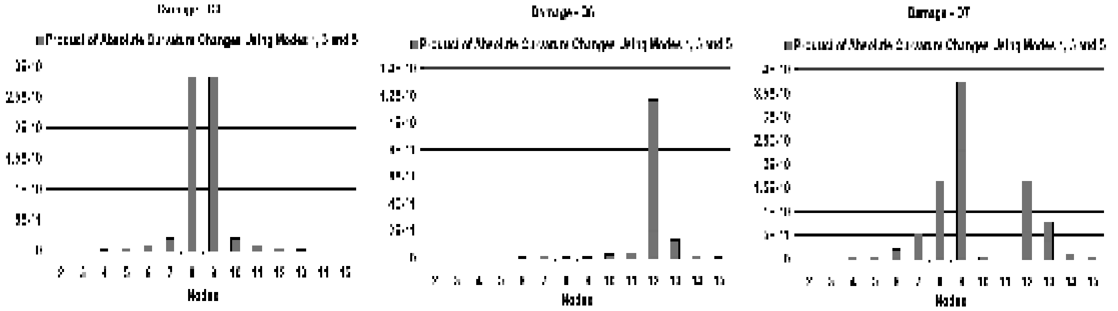
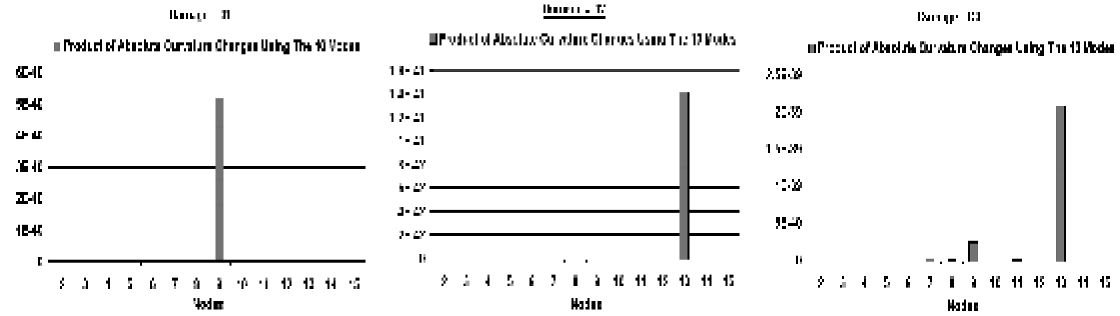


Fig (11): Product of ADC using modes 1,3 and 5



For the different Damage scenarios – Shell elements model
Fig (12): Product of ACC using 10 modes



For the different Damage scenarios – Frame elements model
Fig (13): Product of ACC using modes 1,3 and 5
For the different Damage scenarios – Frame elements model
Fig (14): Product of ACC using 10 modes
For the different Damage scenarios – Shell elements model

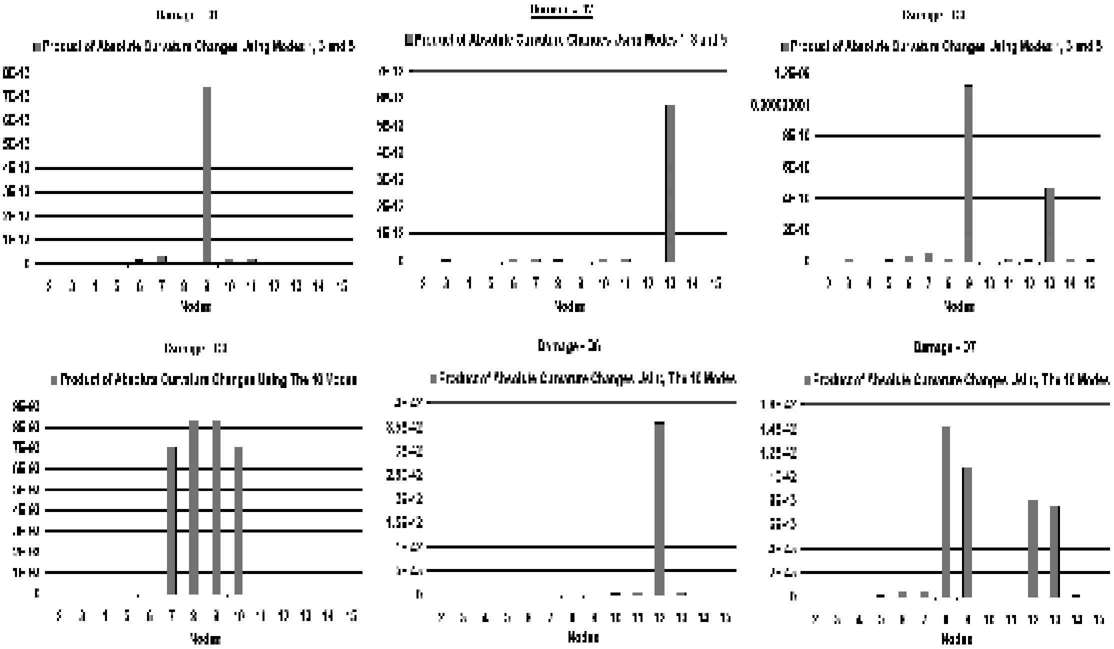


Fig (15): Product of ACC using modes 1,3 and 5
For the different Damage scenarios – Shell elements model

DAMAGE DETECTION OF CABLE-STAYED BRIDGES

The Suez-Canal cable stayed bridge was assumed as a case study to check the validity of damage detection techniques that have been verified in the previous example.

THE SUEZ-CANAL MATHEMATICAL MODEL

A finite element model was created for the bridge using the original drawings that had been prepared by the designers [20]. The model was created using the SAP2000 finite element program. An EMA “Experimental Modal Analysis” test had been done for the bridge and the analysis results were used to update and tune the mathematical model to represent the real bridge [7]. The updated model was used to perform the case study.

THE CASE STUDY SETUP

414 joints were selected to be included in the case study. The selection included all the cables joints and the intermediates at the cross diaphragms of the main bridge girder along its length beside all cables joints and some other joints of the two pylons to cover all the critical sections and elements of the bridge. The selected joints have been classified and grouped according to their location and type to simplify joints tracing [7]. Table (5) shows the assumed damage scenarios and their descriptions and fig (16) shows the damage scenarios locations.

The same proposed automated tool with a little bit modifications was used to perform the analysis [7]. The SAP2000 output data for the undamaged case and all damage scenarios were imported to Excel sheets for the all investigated joints to be used in the analysis. For all damage scenarios related to the main girder the vertical displacements (Z direction) were only used for the analysis, while for those of pylons the horizontal displacements (X direction) were used.

The automated tool gives the ability to use all the investigated joints or some of them based on any selection criteria using joints classification that mentioned before. It means that the selection may include all cables joints, or all non-cables joints, or both, or one side strip . . . etc, and the same for pylons.

ANALYSIS RESULTS

Table (6) shows the modal participation factors (MPF), table (7) shows the first thirty modal frequencies and table (9) shows the calculated Modal Assurance criteria (MAC) for the different damages scenarios.

By studying the results accurately and performing many trails using the three damage location detection techniques, it was found that the best results achieved using modes of biggest MPF (greater than unity for the undamaged case- the shaded records in table (6), which are 5,21 and 27 for Z-direction, 1,11,12,16,20,24,25 and 30 for X-direction.

It was noted that those modes are not necessary to have the lowest MAC or the biggest frequency shifts. For example, the three lowest MAC values of damage scenario D1 are those of modes 14, 17 and 18, which are not effective in the vertical motion, and the biggest frequency shifts of damage scenario D4 are those of modes 1 and 30 that have not a significant contribution in the vertical motion. So the best guide for modes selection is the MPF.

The shaded joints in table (5) represent the damage location for each damage scenario. Figures (17) to (19) shows the analysis output bar charts for the three damage detection techniques, which are COMAC value, product of ACD “Absolute change in Displacement” and product of ACC “Absolute Change in Curvature” for the selected modes, taking into consideration that the optimum result is achieved when the damaged joint has the minimum COMAC value and the maximum product of both ACD and ACC as an indication for the damage location.

ANALYSIS RESULTS EVALUATION

The COMAC technique succeeded to detect the damage location only for damage scenarios D4 and D6 but failed for the others. The COMAC sensitivity is so limited, where the lowest value for both D4 and D6 are 0.99982 and 0.958, which are near to unity (value of undamaged joints) especially by assuming that COMAC should be calculated using EMA results that may lack the enough accuracy.

The product of ACD succeeded to detect the damage location apparently for damage scenarios D1, D3, D5 and D6 with acceptable accuracy, where the damaged joint got the 1st rank for D6, the 2nd for D1 and the 8th for D3, which is good for the single damage scenario. For the multiple damages scenario (D5), it succeeded to detect two damaged joints from the four damaged joints apparently. It is noted that it is effective for mid-span joints that have a considerable change in displacements, unless the change in displacement of a mid-span cable joint is considered as a resultant to damage in the opposite side-span cable, like the D2 case, where joint 7 (the 5th rank) is connected to the opposite mid-span cable of that one connected to joint 96.

The product of ACC technique succeeded powerfully to detect the damage location apparently for all damage scenarios even the multiple damages one as shown in the illustrating charts, where the damaged joints got the 1st rank for all case and with a big difference with respect to the other joints even that of the same damaged member, like case of D6 in fig (19) joint 113 is the second joint of the damaged member that has a plastic hinge at joint 110.

Finally, it is recommended to use the product of ACC technique for damage location detection for cable-stayed bridges, while the other techniques may be considered as helping tools only.

Table (5): Bridge damage scenarios

Damage Scenario	Damage Type	Damage Location	Joint ID	Joint Group	Joint Order	Damage Modeling	Damage Severity
D1	Single	1st Cable at mid-span at east-south quarter	1274	ESDMC	1	Stiffness Reduction	90%
			1275	ESPC	1		
D2	Single	1st Cable at side-span at west-south quarter	96	WSDSC	1	Stiffness Reduction	50%
			8	WSPC	1		
D3	Single	8th Cable at mid-span at west-north quarter	50	WNDMC	1	Stiffness Reduction	70%
			25	WNPC	1		
D4	Single	16th Cable at side-span at east-north quarter	1312	ENDSC	1	Stiffness Reduction	90%
			1311	ENPC	1		
D5	Multiple	All the above					
D6	Single	Vertical Pylon element below the deck at west-south quarter	110	WSPN	1	Plastic Hinge	------
			111	WSPN	1		

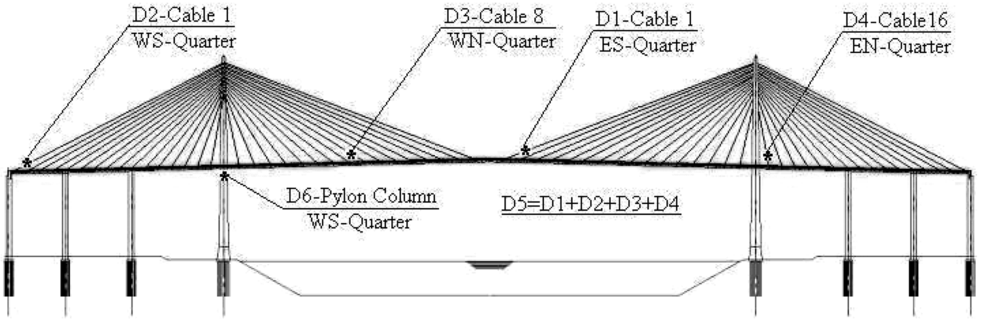


Fig (16): Damage scenarios locations

Table (6): Modal Participation Factors

Case	Intact	D1	D2	D3	D4	D5	Intact	D6
Mode	**Z Displacements**						**X Displacements**	
1	-0.002	-0.075	-0.044	0.004	-0.001	-0.270	-68.589	-68.398
2	-0.001	-0.059	0.003	-0.011	-0.002	-0.063	-0.001	-0.110
3	0.019	0.087	0.044	0.004	0.019	-0.090	-0.007	0.006
4	-0.068	0.202	0.071	0.096	-0.068	-0.245	-0.007	-0.011
5	-22.784	-22.697	-22.784	22.823	-22.784	-22.739	-0.004	-0.513
6	0.017	-0.263	0.105	-0.029	0.017	0.219	0.002	-0.036
7	0.024	0.038	-0.008	-0.045	0.024	-0.037	0.000	-0.054
8	0.017	-0.040	0.008	0.016	0.017	-0.043	0.097	-0.388
9	0.003	0.025	0.010	0.004	0.003	-0.040	-0.099	-0.385
10	-0.005	0.005	-0.002	0.005	-0.005	0.023	0.011	-0.219
11	-0.011	0.055	-0.020	0.008	0.011	-0.106	-19.760	19.841
12	-0.014	0.296	0.141	0.070	0.013	0.542	8.766	-8.774
13	0.091	-0.014	0.079	-0.083	0.091	-0.010	0.039	-0.155
14	-0.002	0.043	-0.003	-0.003	0.001	0.040	0.000	-0.007
15	-0.004	0.005	-0.024	0.031	-0.005	-0.062	0.017	0.133
16	0.001	-0.115	0.054	-0.015	0.001	0.145	3.392	3.477
17	-0.125	-0.060	-0.118	0.120	-0.125	-0.035	-0.111	0.116
18	0.002	0.057	-0.002	-0.023	0.002	0.055	-0.019	0.206
19	0.004	-0.014	0.024	-0.021	-0.004	0.002	0.242	0.270
20	-0.007	0.125	0.056	-0.013	0.007	0.187	-21.147	21.086
21	-4.657	-5.035	4.641	4.682	4.657	5.020	-0.130	0.382
22	-0.009	-0.388	0.051	0.028	-0.008	-0.358	0.075	-0.132
23	-0.032	0.031	0.040	0.037	-0.031	0.030	-0.002	0.125
24	-0.008	-0.033	-0.018	-0.166	-0.006	1.814	-20.429	21.565
25	0.094	0.086	-0.099	-0.044	0.097	-0.024	1.070	-0.892
26	0.063	-0.319	0.175	0.627	0.073	-1.303	-0.086	-0.366
27	-9.780	-9.721	-9.751	-9.662	9.780	9.074	0.118	2.125
28	-0.171	0.133	0.180	-0.153	-0.172	-0.063	-0.228	0.233
29	-0.279	-0.248	-0.255	-0.153	-0.278	0.031	0.051	0.053
30	0.029	0.169	0.068	-0.224	0.026	-0.971	-12.785	-12.576

Table (7): Modal Frequencies

Case	**Intact**	**D1**		**D2**		**D3**		**D4**		**D5**		**D6**	
Mode	**F Hz.**	**F Hz.**	**Δ %**	**F Hz.**	**Δ %**	**F Hz.**	**Δ %**	**F Hz.**	**Δ %**	**F Hz.**	**Δ %**	**F Hz.**	**Δ %**
1	0.255	0.255	-0.03%	0.255	-0.02%	0.255	0.00%	0.255	-0.01%	0.254	-0.56%	0.254	-0.50%
2	0.268	0.268	-0.01%	0.268	0.00%	0.268	0.00%	0.268	0.00%	0.268	-0.01%	0.268	0.01%
3	0.348	0.348	-0.01%	0.348	0.00%	0.348	0.00%	0.348	0.00%	0.348	-0.01%	0.348	0.00%
4	0.367	0.367	0.00%	0.367	0.00%	0.367	0.00%	0.367	0.00%	0.367	0.00%	0.367	0.00%
5	0.403	0.400	-0.78%	0.402	-0.28%	0.402	-0.14%	0.403	0.00%	0.397	-1.36%	0.402	-0.15%
6	0.436	0.436	-0.01%	0.436	0.00%	0.436	0.00%	0.436	0.00%	0.436	-0.02%	0.436	0.00%
7	0.461	0.461	0.00%	0.461	0.00%	0.461	0.00%	0.461	0.00%	0.461	0.00%	0.461	0.00%
8	0.496	0.496	-0.01%	0.495	-0.14%	0.496	0.00%	0.496	0.00%	0.495	-0.12%	0.496	0.01%
9	0.498	0.498	-0.02%	0.498	-0.14%	0.498	0.00%	0.498	0.00%	0.497	-0.15%	0.498	0.00%
10	0.498	0.498	0.01%	0.498	0.00%	0.498	0.00%	0.498	0.00%	0.498	0.00%	0.498	0.01%
11	0.499	0.499	0.00%	0.499	0.01%	0.499	0.00%	0.499	0.00%	0.499	-0.01%	0.499	0.00%
12	0.556	0.555	-0.13%	0.556	-0.11%	0.554	-0.38%	0.556	0.00%	0.552	-0.69%	0.556	-0.05%
13	0.563	0.562	-0.11%	0.563	0.05%	0.563	-0.02%	0.563	0.00%	0.562	-0.07%	0.563	0.05%
14	0.564	0.564	-0.03%	0.564	0.02%	0.564	0.00%	0.564	0.00%	0.564	-0.01%	0.564	0.02%
15	0.564	0.564	0.10%	0.565	0.20%	0.564	0.02%	0.564	0.00%	0.566	0.43%	0.564	0.12%
Case	**Intact**	**D1**		**D2**		**D3**		**D4**		**D5**		**D6**	
Mode	**F Hz.**	**F Hz.**	**Δ %**	**F Hz.**	**Δ %**	**F Hz.**	**Δ %**	**Mode**	**F Hz.**	**F Hz.**	**Δ %**	**F Hz.**	**Δ %**
16	0.570	0.570	-0.02%	0.570	0.06%	0.570	-0.06%	0.570	0.00%	0.571	0.12%	0.570	0.04%
17	0.576	0.576	-0.12%	0.577	0.06%	0.576	-0.01%	0.576	0.00%	0.576	-0.08%	0.576	0.03%
18	0.577	0.577	0.02%	0.577	0.05%	0.577	0.02%	0.577	0.00%	0.577	0.04%	0.577	0.04%
19	0.577	0.578	0.05%	0.578	0.11%	0.577	0.00%	0.577	0.00%	0.579	0.32%	0.577	0.04%
20	0.588	0.588	-0.02%	0.589	0.05%	0.588	-0.10%	0.588	0.00%	0.588	0.00%	0.588	0.03%
21	0.733	0.727	-0.74%	0.732	-0.01%	0.732	-0.11%	0.733	0.00%	0.726	-0.93%	0.732	-0.06%
22	0.737	0.737	-0.01%	0.737	0.00%	0.737	0.00%	0.737	0.00%	0.737	-0.10%	0.737	0.01%
23	0.803	0.803	0.01%	0.803	0.00%	0.803	-0.01%	0.803	0.00%	0.803	-0.01%	0.803	-0.01%
24	0.922	0.922	0.01%	0.922	-0.01%	0.921	-0.02%	0.922	0.00%	0.911	-1.17%	0.912	-1.09%
25	0.926	0.926	0.00%	0.926	0.00%	0.926	0.00%	0.926	0.00%	0.926	-0.01%	0.926	0.00%
26	0.952	0.951	-0.05%	0.950	-0.16%	0.951	-0.08%	0.952	0.00%	0.950	-0.24%	0.952	0.01%
27	0.981	0.978	-0.38%	0.981	-0.02%	0.976	-0.54%	0.981	0.00%	0.963	-1.84%	0.971	-1.06%
28	1.032	1.032	0.01%	1.032	0.00%	1.032	0.00%	1.032	0.00%	1.032	0.02%	1.032	0.00%
29	1.032	1.032	-0.01%	1.032	0.00%	1.032	-0.01%	1.032	0.00%	1.032	-0.02%	1.032	-0.01%
30	1.151	1.150	-0.12%	1.151	-0.03%	1.150	-0.11%	1.151	-0.02%	1.134	-1.50%	1.136	-1.30%

Table (8): MAC values

Mode	D1	D2	D3	D4	D5	D6
1	0.98055	0.99595	0.99990	0.99996	0.88757	0.99989
2	0.99684	1.00000	0.99987	1.00000	0.99637	0.99349
3	0.91114	0.99564	0.99583	1.00000	0.91520	0.98205
4	0.99066	1.00000	0.99962	1.00000	0.98417	0.99445
5	0.99973	0.99996	0.99989	1.00000	0.99914	0.99958
6	0.73778	0.96106	0.98193	0.99999	0.79110	0.99981
7	0.99997	0.99979	0.99986	1.00000	0.99995	0.99988
8	0.92180	0.57853	0.99813	1.00000	0.65251	0.96877
9	0.27068	0.04646	0.96848	0.99998	0.05137	0.36863
10	0.61208	0.57998	0.91476	0.99999	0.72211	0.93815
11	0.99698	0.98961	0.99952	1.00000	0.98865	0.99981
12	0.99976	0.99992	0.99961	1.00000	0.99906	0.99947
13	0.09354	0.53454	0.90482	0.99978	0.08608	0.87114
14	0.00026	0.02755	0.00644	0.23738	0.00127	0.67419
15	0.16265	0.19503	0.19988	0.99177	0.19938	0.19030
16	0.99982	0.99986	0.99954	1.00000	0.99736	0.99718
17	0.00050	0.46074	0.99722	0.99999	0.00464	0.99137
18	0.01248	0.00903	0.03096	0.99991	0.01901	0.31243
19	0.25887	0.63340	0.70074	0.99993	0.67956	0.75027
20	0.99986	0.99994	0.99949	1.00000	0.99891	0.99746
21	0.99879	0.99999	0.99976	1.00000	0.99867	0.99956
22	0.38357	0.99282	0.98904	0.99996	0.02823	0.97667
23	0.99995	1.00000	0.99999	1.00000	0.99984	0.99971
24	0.99998	0.99950	0.99857	1.00000	0.91827	0.97462
25	0.99478	0.99113	0.98169	0.99975	0.91276	0.99880
26	0.99945	0.99979	0.99752	1.00000	0.99190	0.99942
27	0.99631	0.99907	0.98739	1.00000	0.89875	0.95703
28	0.93441	0.99879	0.99908	0.99998	0.71260	0.96884
29	0.99530	0.99911	0.99603	1.00000	0.83527	0.97107
30	0.99928	0.99993	0.99973	0.99999	0.98996	0.92468

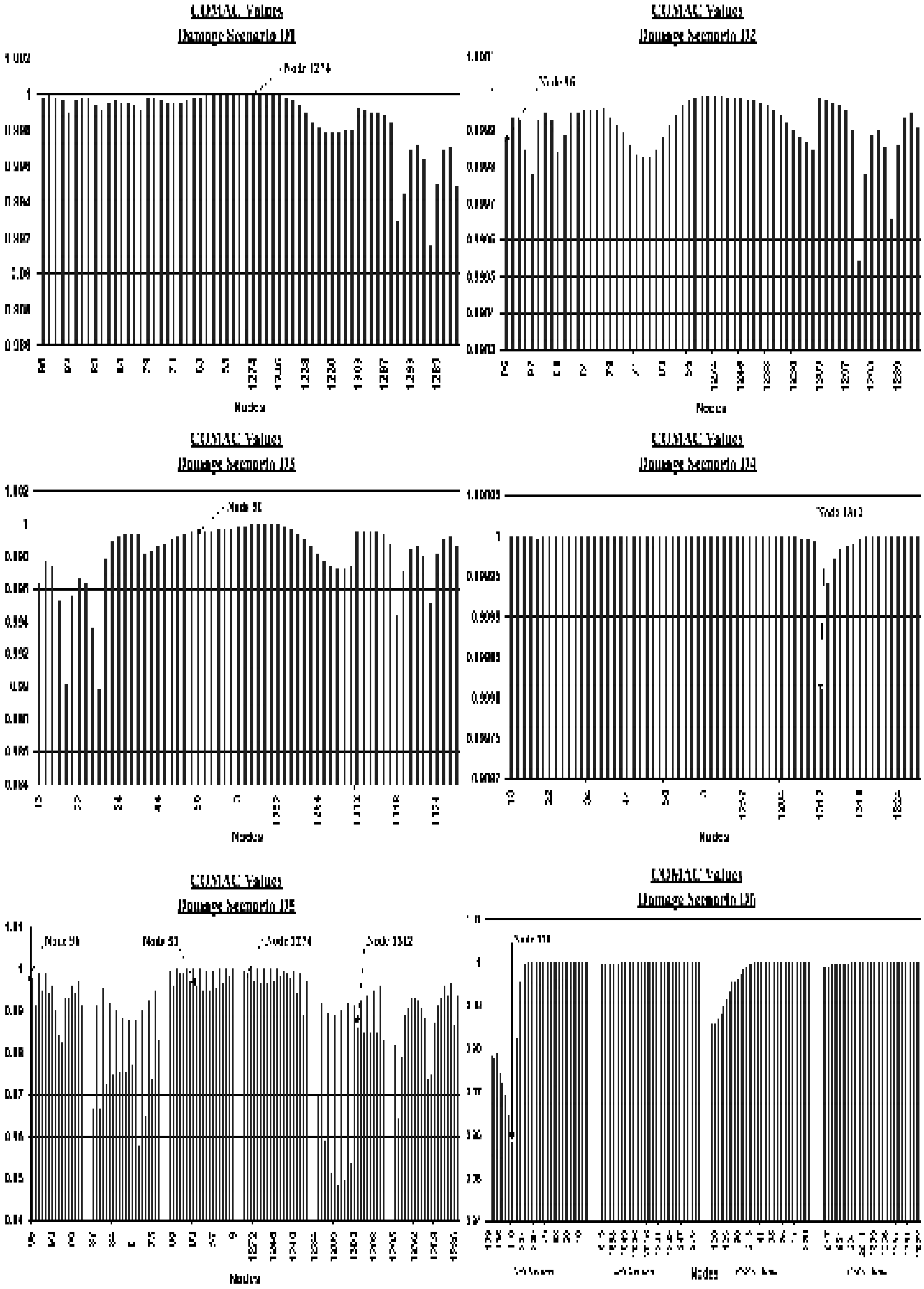


Fig (17): COMAC values for the different

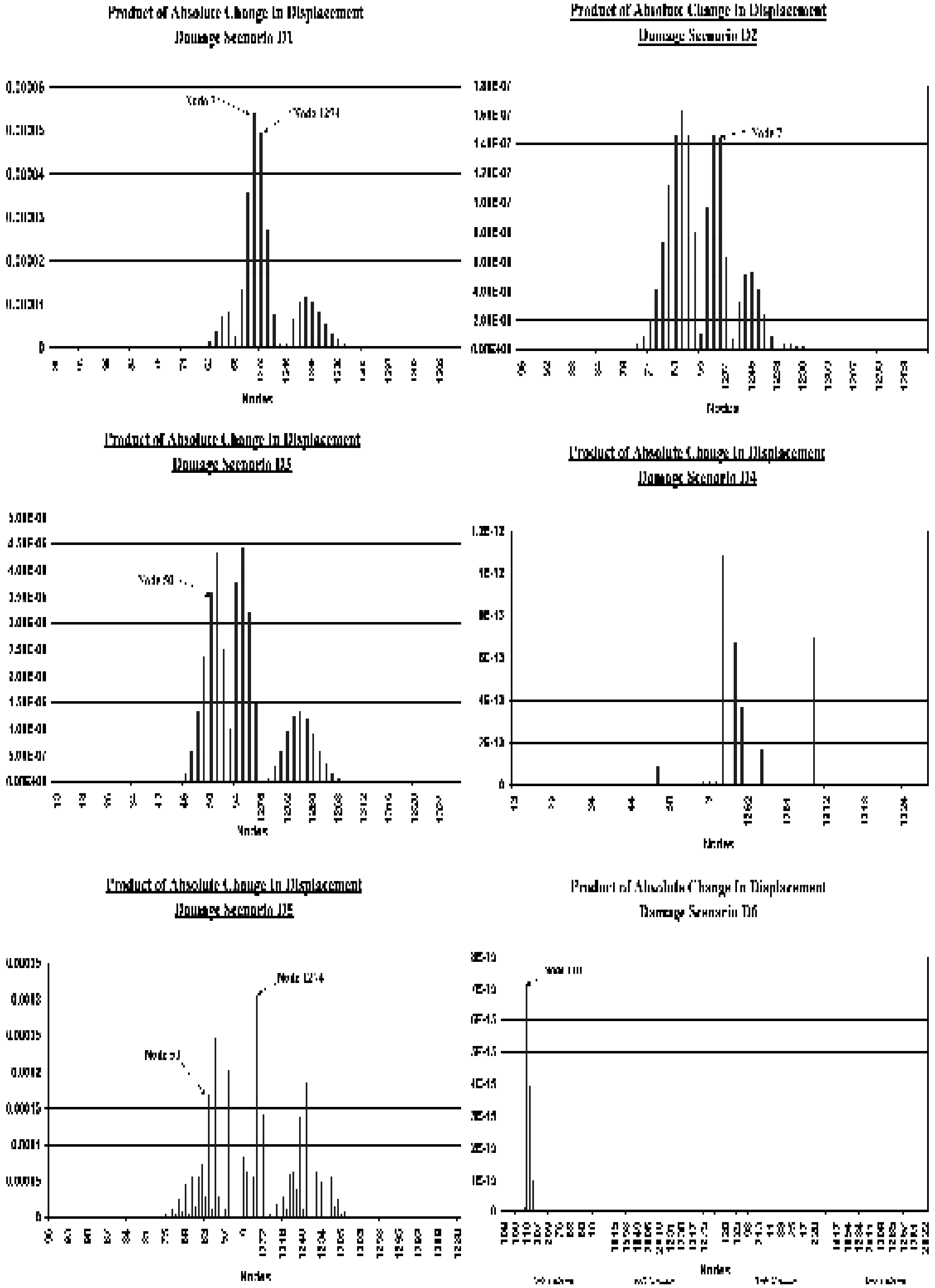


Fig (18): Product of ACD values for the different damage scenarios

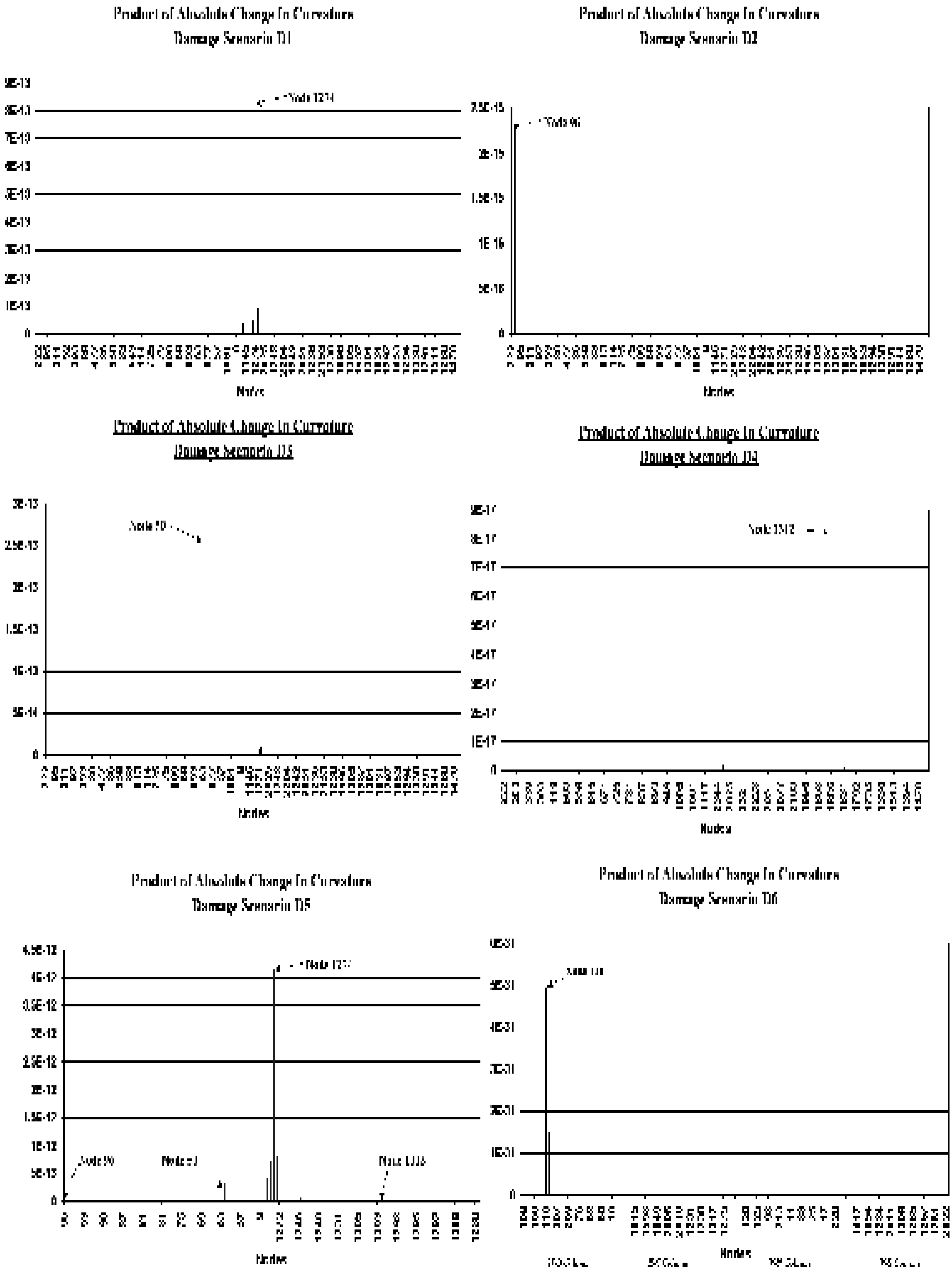


Fig (19): Product of ACC values for the different damage scenarios

CONCLUSION

Three different damage identification methods were introduced by the help of a proposed technique and a computerized analysis tool that simplifies the very complicated calculations required for the three methods. The three methods were verified using a simple beam and then implemented for the Suez-Canal cable-stayed bridge as a case-study. The results led to the following:

- The structural health monitoring systems of cable-stayed bridges can depend on those damages detection techniques that based on changes in basic modal properties (natural frequencies and mode shapes).
- Structure and damage modeling techniques have a great effect on the results, where in the simple beam study, modeling the beam using shell elements and the damage as a crack gave more accurate results than those of modeling the beam using frame elements and the damage by stiffness reduction.
- Mode shapes are more sensitive damage indicators than frequencies of vibration especially for low damage severities, so changes in the natural frequencies could be used only as global indications for damage existence for cable-stayed bridges, but they could not be used for damage location identification.
- Damage location detection techniques based on changes in mode shapes are more suitable for cable-stayed bridges on two conditions, normalization of mode shapes pairs with respect to masses and frequencies and selecting the most appropriate modes for the analysis; where using all modes pairs may masks the damage location identification. Mode shapes of both undamaged (Intact) and damaged cases are normalized by multiplying the modes shapes ordinate by the modal participation factors (MPF) and divided by frequencies. Modes selection may be based on assuming those modes of the highest frequency shifts, or those of the lowest MAC values or those of the highest MPF in the studied direction; and the last was found the best accurate selection.
- The modal assurance criteria (MAC) is used as indication for damage existence only, while the coordinate modal assurance criteria (COMAC) may be used for damage location identification. COMAC implementation in both the simple beam and the Suez-Canal Bridge case studies gave incorrect indications for damage location for both single and multiple damage scenarios, so it may be used only as a secondary tool to differentiate between two or three locations for the damage that were previously identified by another accurate method.
- The product of changes in displacements technique is more accurate than the COMAC technique only in single damage scenario but finally it also gave unsatisfactory results in both the simple beam and the Suez-Canal Bridge case studies, so it may be used also as a secondary tool.
- The product of changes in curvatures technique gave very accurate results for damage location identification for both single and multiple damage scenarios in both the simple beam and the Suez-Canal Bridge case studies, so it may be considered the most accurate and appropriate technique (based on mode shapes changes) for damage location identification of cable-stayed bridges.
- In the simple beam study, calculating the exact curvature of a point using the 6th order polynomial function fitting for a mode shape gave approximately the same result using the central difference approximation of the Taylor series method, which was used in the Suez-Canal Bridge study.
- The damage severity could be calculated by plotting the relation between the member damage severity and the MAC value of the most affected mode by the damage.

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