Modal Parameters for Structural Integrity Monitoring of Fixed Offshore Platforms

by V.G. Idichandy and C. Ganapathy

ABSTRACT—The most commonly used offshore oil-production platforms, the jacket structures, because of their long service in a very hostile environment, require periodic inspection for structural integrity. Present-day diver inspection is highly uneconomical and has certain inherent limitations. To overcome these limitations, it has been proposed to use an instrumented monitoring system based on the dynamic response of the platform. Several investigations were carried out to remove the uncertainties in this method which arose mainly from changes in the mass on the deck and marine growth. One of the important proposals investigated was the use of modal vectors. But these investigations were based on simple analytical and physical models. In order to assess the efficiency of using modal vectors to monitor the structural integrity of the platform, a detailed study was carried out on a real platform. Finite-element and physical models of the platform were used in the investigation. This paper reports on the physical model tests. A geometric model of the platform was tested under electrodynamic and wave excitation, simulating damages in the structure and changing the mass on the deck. In all tests, modal frequencies and modal vectors in different degrees of freedom were determined by autospectral analysis of acceleration response. Based on the results, a scheme for integrity monitoring of a fixed offshore platform is suggested which, if implemented carefully, can at least minimize, if not dispense with, the uneconomic diver inspection.

Introduction

Most of the offshore oil-production platforms are jacket-type fixed structures, a welded-steel tubular space frame. Despite all the precautions taken during the design, fabrication and installation stages, long service in a very hostile environment makes it mandatory to inspect these structures to identify and locate possible structural defects for timely maintenance and repairs. Such inspections are now carried out by divers. But poor visibility, concealment of damages by marine growth, prohibitive cost, nonavailability of properly trained divers and dependence of diver inspection on weather conditions limit the viability of this operation technically and economically. Consequently, a need was felt to develop better and reliable techniques, preferably operated from the deck of the platform, to monitor the structural integrity of the installation periodically. A method based on the dynamic response of the structure was found to be most promising, since it had already been successfully used on structures after fire hazards and local seismic activity.

The method is based on the fact that any structure has natural modes of vibration which are fundamental properties of the structure and do not change unless there are changes in the stiffness or mass distribution. In the case of an offshore structure, these modes are continuously excited by wind and wave forces and periodic determination of modal characteristics with the help of proper instrumentation and measurement techniques can be helpful in revealing the defects reducing the structural stiffness. Thus it may appear that integrity monitoring is a simple exercise of determining modal parameters of the platform. But then there are factors other than structural damages such as change in mass distribution that could also alter modal characteristics, leading to erroneous conclusions while interpreting the measured data. Consequently, any investigation in this area should primarily address the removal of the uncertainties in interpreting the measured data.

Because of the importance of the topic, certification agencies, research establishments on behalf of the oil industry and universities are engaged in research in this area. Investigators have used analytical and physical models of platforms. Also many have made field measurements on actual platforms, although the viability of the technique could not be established based on these published works. Bombassei[1], Coppolino,[2] Duggan,[3,4] Kenley,[8] Loland,[9], Nataraja,[10] Vandiver,[12,13] Wojnarowski[14] and Yang[15] have presented some of the important studies in this area. While most of the investigators concentrated on shift in natural frequencies, as it could be easily measured from the deck, Rubin and Coppolino[11] and Bouwkamp[2] suggested the changes in modal vectors in different degrees of freedom as more sensitive to damages. However, these authors based their conclusions on simple analytical and physical models and suggested further detailed study using three-dimensional finite-element models of actual platforms to fully develop the potential of their suggestions. However, based on the available results, it could be concluded that shift in natural frequencies alone would not provide enough information for integrity monitoring, unless the failure was in one of the

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most important load-bearing members. Therefore, it was necessary to study the problem in detail as suggested by Rubin and Bouwkamp and it was decided to use an actual platform for the study.

Analytical Investigation—A Brief Outline

A well platform in a water depth of 85 m was selected for the analysis. It had eight piles: four main and four skirts and the overall height from mud level to the top deck was 107 m. A finite-element model of the platform was formulated idealizing the members as three-dimensional beam elements having all six degrees of freedom at each node. Except for some very unimportant members, almost the entire structure was represented. Additional mass due to equipment on deck, grout in the pile leg annular space, water inside the pile and the effect of added mass were all lumped at the respective nodes. The pile foundation was simulated in the model by the boundary elements of stiffness computed from the soil data of the location of the platform. An excessive marine growth as expected in tropical waters was also represented as additional lumped mass. The final model with 253 nodes, 373 beam elements and 88 boundary elements was analyzed using FEM. A detailed parametric study varying deck mass, changes in foundation simulating scour or soil buildup, marine growth and damages in members such as complete severance or half-through crack were carried out individually and in different combinations to determine the influence of these changes on natural frequencies and mode shapes of the structure. The details of this study are given in Refs. 6 and 7.

Results of the Analytical Study

The general conclusions from the analytical study were the following. Changes in deck mass or distributed mass which affected the structure as a whole, resulted in shifts in natural frequencies in all the modes; whereas, the severance of an important load-bearing member affected only those modal frequencies for which the severed member was of consequence. Complete severance of redundant members at horizontal level had no effect on the natural frequencies. Even for failure of some load-bearing bracings, the order of shift in natural frequency was almost the same as due to, say, five-percent change in deck mass. In other words, integrity monitoring based on frequency shift alone becomes impractical on platforms where there are unaccounted changes in mass either on deck or on structure, unless the severed member is a very important load-bearing member and the nonuniform changes in frequencies of different modes provide the necessary clue for the presence of structural damages.

Changes in deck mass, scour or soil buildup did not change the mode shapes considerably. Even the minor changes in deck mass did not affect the basic form of the mode shape. However, excessive marine growth as assumed in this investigation, altered the mode shape retaining the basic form unchanged. The results indicate that changes in mass and foundation affected the structure as a whole. This is in sharp contrast to the changes in mode shapes when structural damages were present. There were drastic changes in the affected mode shapes especially in the neighborhood of the damages. However, the dominant mode shapes remained unaltered when there was failure in redundant members at the horizontal levels. The above conclusions were true even when the damages were studied in combination with changes in other parameters. In other words, changes in mode shapes due to structural damages persisted even in the presence of changes in other parameters affecting dynamic response.

It has also been established from this investigation that modal vectors perpendicular to the dominant modal direction were very sensitive to damages. The changes in these values were very drastic; often the values changed by a few hundred percent. Even in the presence of changes in parameters other than damages, these values remained very much different when damages were present. Another interesting factor noticed was the dependence of these vectors on damages in redundant members. At higher modes, modal vectors near the failure changed considerably even for highly redundant horizontal level members. It may be interesting to note that higher modes do get excited in offshore platforms under ambient conditions. Twenty-four modes were identified in a platform in one of the field measurements as reported in Ref. 3.

Objectives of the Experimental Investigation

For the model study, verification of the analytical results was one of the major objectives. In addition, it was necessary to establish the measurements procedure to obtain all the parameters under ambient excitation conditions. For this limited purpose, test on a geometrically similar model, an analysis of the same by FEM and a comparison of the results obtained should be adequate and sufficient. Moreover, it is almost impossible to design an elastic model of a jacket platform with available materials and testing methods, especially when the model is tested under hydrodynamic loading.

Design and Fabrication of the Model

Though an exact elastic modeling for hydrodynamic loading was not attempted because of the limited objectives, the model was designed with certain characteristics. (1) The water depth of the random wave flume where some of the tests were held was 2.5 m. To simulate the prototype water depth, the linear scale factor had to be 1:35. (2) To simulate the wave-force loading on the model, Froude's law was the basis for model design. A model designed according to Froude's law has a fundamental period in the ratio of the square root of the linear scale factor. To satisfy this condition, the model had a fundamental period of 3.32 Hz representing the prototype frequency of 0.52 Hz.

To accomplish these guidelines, it was decided to scale down all possible dimensions by the linear scale factor 1:35 and to choose a model material of low Young's modulus compared to steel, the prototype material. Though it would have been ideal if such a material had been available with higher density than that of the prototype material to simulate Froude's criteria completely, it was found that the same effect could be achieved by lumping masses in the model without affecting the stiffness. In this case, however, the distributed mass was simulated by flooding the main legs and adding appropriate deck mass. This naturally resulted in a higher natural frequency for the model in air which was brought down to some acceptable level by additional deck mass.

Polyvinyl chloride was selected as the model material as it satisfied the conditions described and also because of its availability in tubular form and easy workability. Outer diameters of the tubular members were selected satisfying the linear scale factor depending on availability. For instance, the outer diameter of the main leg was 0.04 m in the model scale corresponding to 1.35 m in the prototype. All bracings on the vertical faces were from tubes of outer diameter 0.02 m. All horizontal bracings were of outer diameter 0.016 m. Unlike the prototype structure, only two diagonals were provided in the horizontal level bracings for ease of fabrication. The complicated bracings in the horizontal levels in the prototype were more functional in supporting the risers than in adding to the overall stiffness of the structure.

Individual members cut to exact dimensions satisfying the scale factor 1:35 were joined together with the help of a chemical compound used to join PVC tubes. Each joint was very carefully done to ensure proper load transfer. A deck structure of scaled-down dimensions was fabricated and fixed. Perspex plates were placed on the main and cellar deck to support additional deck loads.

Figure 1 shows the key plan of the model and the coordinate system adopted for analysis. Some of the important dimensions are shown in the FE model used for dynamic analysis (see Figs. 5 and 6).

Test Program

Ideally all the tests on the model had to be done in the wave flume under hydrodynamic loading. However, considering the water depth in the flume (2.5 m) and the difficulty in simulating damages in submerged members as well as rejoining them for further damages in other members, it was decided to restrict the number of experiments to be done in the flume to a minimum and carry out tests involving damages in more members in air by dynamic loading with an electrodynamic excitor. Here it may be noted that all the results obtained were modal characteristics of the model and were independent of the excita-

TABLE 1—NATURAL FREQUENCIES OF THE MODEL—COMPARISON OF RESULTS

Deck Mass	Condition of Model	FEM		Experimental	
		I x-flexure (Hz)	II x-flexure (Hz)	I x-flexure (Hz)	II x-flexure (Hz)
M	No damage	5.727	30.59	5.15	27.5
M	145 missing	5.708 (0)	29.53 (−3.5)	5.10 (0)	26.2 (−4.7)
M	114 half-through crack	5.704 (0)	29.71 (−2.9)	5.15 (0)	26.5 (−3.6)
M	114 missing	5.556 (−3.0)	24.13 (−21.1)	4.9 (−4.9)	21.0 (−23.6)
M	86 missing	5.576 (−2.6)	30.22 (−1.2)	5.05 (−1.9)	27.0 (−1.8)
M	104 missing	5.727 (0)	30.57 (0)	5.15 (0)	27.5 (0)
M + 10 percent	No damage	5.457 (−4.7)	30.43 (0)	4.95 (−4.9)	27.0 (−1.8)
M + 10 percent	145 missing	5.443 (−5.0)	29.46 (−3.7)	4.85 (−5.8)	25.8 (−6.2)
M + 10 percent	114 half-through cut	5.438 (−5.1)	29.58 (−3.3)	4.9 (−4.9)	26.0 (−5.5)
M + 10 percent	114 missing	5.297 (−7.5)	24.08 (−21.3)	4.65 (−9.7)	20.5 (−25.5)
M + 10 percent	86 missing	5.334 (−6.9)	30.03 (−1.8)	4.90 (−4.9)	26.5 (−3.6)
M + 10 percent	104 missing	5.457 (−4.7)	30.40 (0)	4.95 (−3.9)	27.0 (−1.8)
M − 10 percent	No damage	6.044 (5.5)	30.78 (0)	5.4 (4.9)	27.0 (−1.8)
M − 10 percent	145 missing	6.024 (5.2)	26.69 (−2.9)	5.38 (4.5)	26.0 (−5.5)
M − 10 percent	114 half-through crack	5.855 (2.2)	29.88 (−2.3)	5.22 (1.4)	27.0 (−1.8)
M − 10 percent	114 missing	6.019 (5.1)	24.27 (−20.7)	5.40 (4.9)	21.25 (−22.7)
M − 10 percent	86 missing	5.903 (3.1)	30.40 (0)	5.30 (2.9)	27.0 (−1.8)
M − 10 percent	104 missing	6.044 (5.5)	30.75 (0)	5.40 (−4.9)	27.0 (−1.8)

Values in bracket indicate percent change.

tion. However, for comparison of results, suitable modification in the finite-element model became necessary to simulate the effects of the model fixed in water for all cases under hydrodynamic loading.

Consequently, tests were conducted for five different damage situations in air under electrodynamic excitation and two under hydrodynamic loading. In both these deck mass alone was varied, as it was discovered in the analysis that changes in mass either on the deck or on the structure contributed the most uncertainty to the interpretation of the measurements.

Test Setup—Dynamic Excitation

The model was fixed on a rigid frame firmly bolted to the test floor. An electrodynamic excitor was used to excite the model at still water level. The load applied on the model was measured with the help of a ring-type load cell. Six accelerometers were fixed at the nodal points of the model on one of the main legs. For additional information, strains were measured at five nodal points. Outputs of the accelerometers were connected to a signal analyzer for auto spectral analysis of the data obtained. The signal analyzer had two independent channels; therefore experiments were repeated to obtain all the data by comparison with one of the points. Figure 2 shows the schematic diagram of the setup. Figure 3 shows the test setup.

Measurements

With an additional deck load of 10 kg the fundamental frequency of the model was around 5 Hz and all the experiments were done with this as the base. Natural frequencies and mode shapes were determined by free vibration, forced excitation and auto-spectral-analysis acceleration response to an arbitrary load (e.g., a triangular wave of 2 Hz). In all cases, the results obtained by the three different methods were in very close agreement with a maximum difference of 0.5 percent. All measurements were restricted to the first two flexural modes in the x direction.

Modal vectors perpendicular to the dominant modal direction were obtained by fixing the accelerometer perpendicular to the x direction at the nodal point of interest. Autopower of both the accelerometer outputs were taken simultaneously for the same load.

All these experiments were repeated for five damage situations and by changing the deck load ± 10 percent. The simulated damage was a half-through crack in member 114 and removal of members 86, 104, 114 and 145 (refer to Figs. 5 and 6 for the location of members).

Tests Under Hydrodynamic Loading

The model was rigidly fixed on the floor of a 4-m wide random-wave flume to be excited under wave action. All the measuring points were the same as in the previous case. Since the accelerometers used in the first experiment were not water protected, cantilever-type strain-gage accelerometers were designed and fabricated specially for this purpose. The wave flume was equipped with a random-wave generator.

In these experiments too, natural frequencies, mode shapes, modal vectors perpendicular to dominant modal

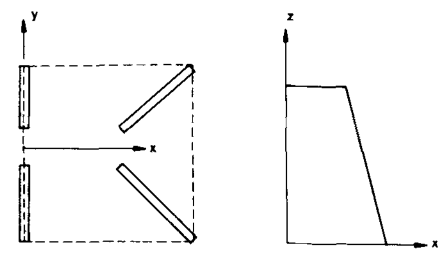

Fig. 1—Key plan of jacket model

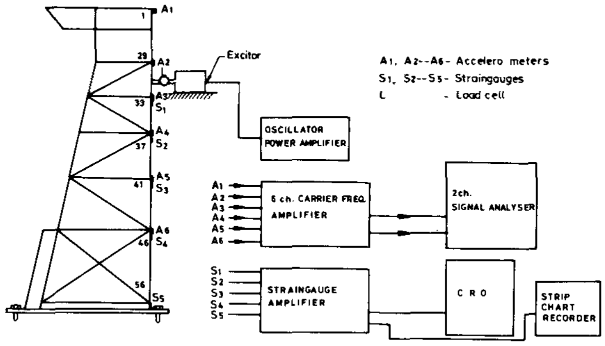

Fig. 2—Schematic diagram of experimental setup (dynamic excitation in air)

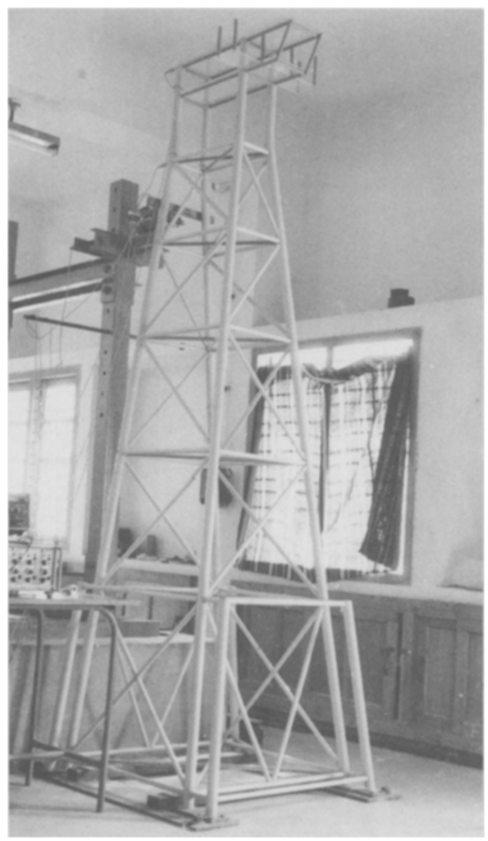

Fig. 3—Test setup, electrodynamic excitation

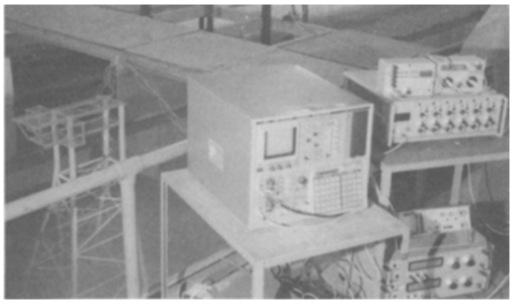

Fig. 4—Test setup, wave excitation

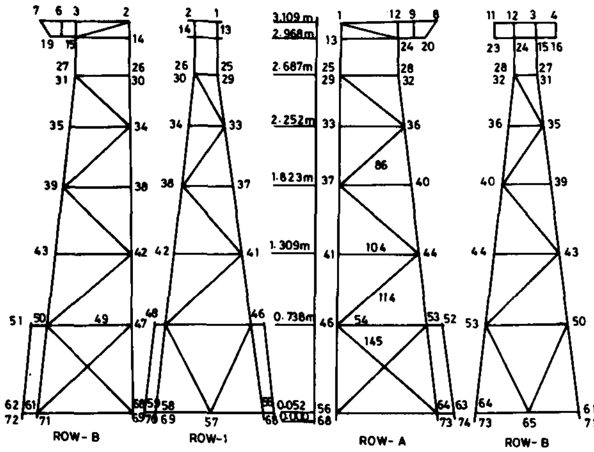

Fig. 5—Vertical framing of jacket model

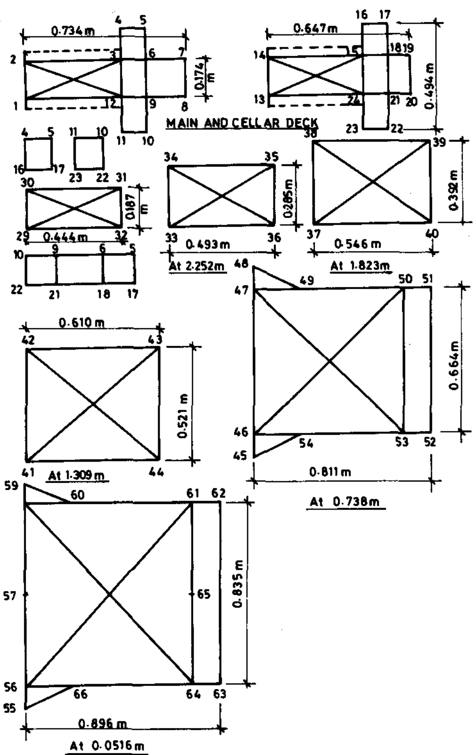

Fig. 6—Deck and horizontal framings at different levels of jacket model

direction and strains were measured as in the previous case. Waves of periods 1.5, 2 and 3 s, and of heights varying from 10 to 20 cm were used for all tests. A random-wave excitation was also used. Auto-spectral analysis of the acceleration response was taken in all cases. Figure 4 presents the test setup and a view of the model fixed in the flume.

Damages were simulated only on two members: 86 and 114; the first near the still water level and the second 1.75 m below. Deck mass was varied by increasing the mass by 2 kg.

Dynamic Analysis of the Physical Model

As in the case of the well platform, a finite-element model of the physical model was formulated for dynamic analysis. The principles governing the modeling were exactly the same in the prototype platform. There were on the whole 74 nodal points and 170 beam elements. The model was assumed to be fixed at eight points at mudlevel. The free-vibration problem was solved for ten eigenvalues. For this analysis, complete removal of the members was simulated by very low values (10^{-15}) for all the section properties of the removed element. All analyses were carried out for ± 10-percent changes in deck mass.

For analyzing the model fixed in water, two modifications in the data were made. They were the effects of water inside the main legs as well as added mass of the submerged members.

Figures 5 and 6 show the finite-element model used for the analysis.

Results Obtained

Table 1 presents the natural frequencies of the first two flexural modes in the x direction (I X and II X) for different conditions obtained from the experiments and analysis. Table 2 presents these results for the model fixed

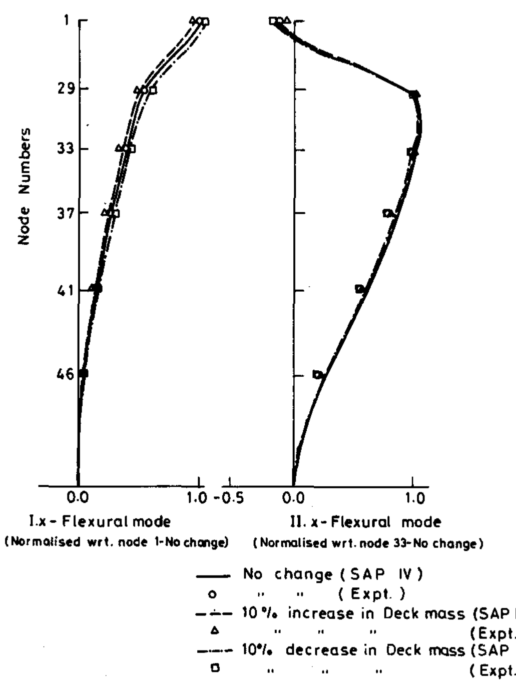

Fig. 7—Mode shapes, effect of deck-load variation

in water. Figures 7-11 and 13-15 show the mode shapes of the model for various conditions along with variations in deck mass.

Strains recorded on the model are presented in Figs. 12 and 17. Table 3 presents the ratio of modal vectors in the x and y directions. Table 4 presents the same for above water nodes when the model is fixed in water. In Fig. 16, the modal vectors perpendicular to the dominant modal direction are plotted. All these results are plotted with self-explanatory notes.

Discussion of Results

Natural Frequency and Structural Damages

Judging from the results of this study, the experimental results compared fairly well with the analytical results.

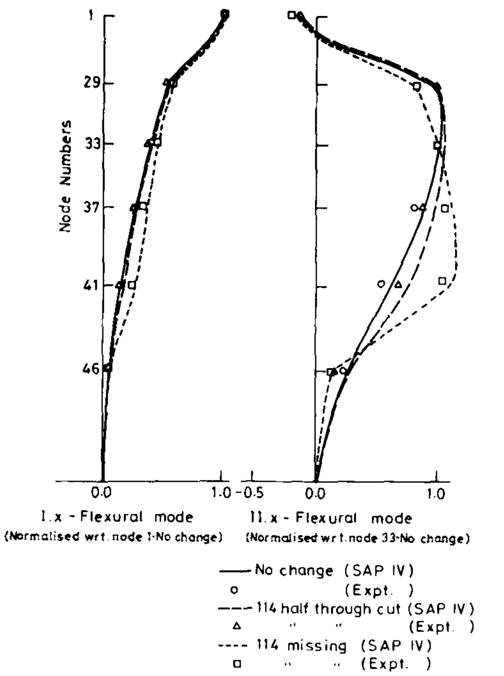

Fig. 8—Mode shapes, effect of damage in model

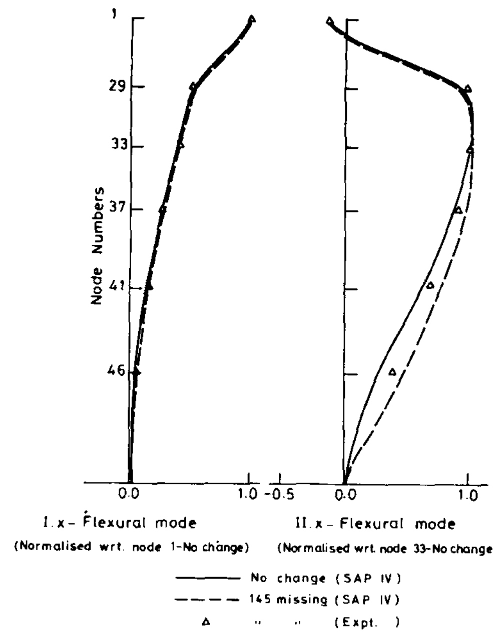

Fig. 10—Mode shapes, effect of damage in model

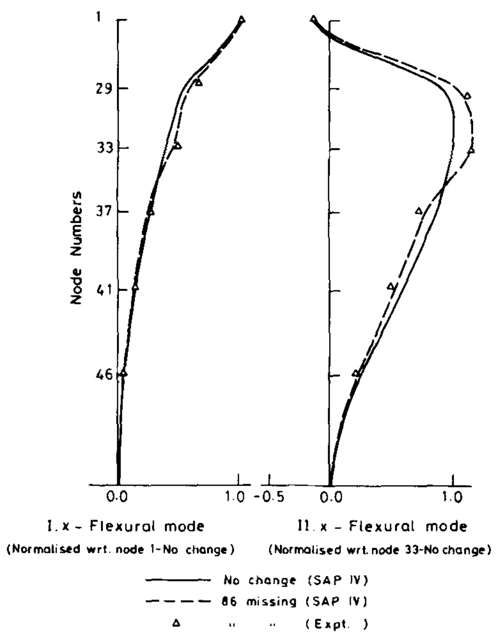

Fig. 9—Mode shapes, effect of damage in model

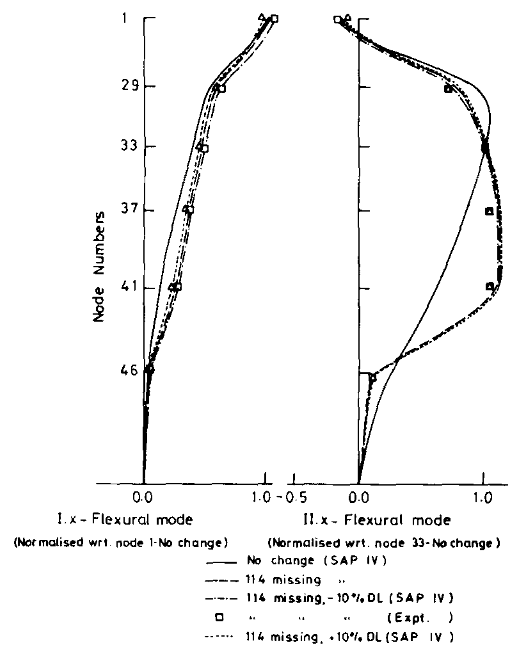

Fig. 11—Mode shapes, combined effect of deck load and damage in model

The results of analyses and experiment as far as frequencies were concerned differed by around ten percent with experimental results giving lower values. This difference is present even when the model was fixed in water. However, the changes in frequencies, caused by structural damages or change in deck mass show the same order of magnitude both for analytical and experimental results. For example, when member 114 was removed, the analytical model registered changes of 3 and 21.2 percent for the first and the second flexural modal frequencies respectively. The corresponding changes in the physical model were 4.9 and 23.6 percent. These values, when the model was fixed in water, were 5.63 and 23.65 percent for the analytical model and 5.4 and 26.4 percent for the physical model respectively. This observation holds good for changes in deck mass also (see Tables 1 and 2).

The ability of the analytical model to predict the natural frequencies of all modes exactly is very important in the implementation of this method for a prototype structure especially when the structure is already in existence for many years and no data on the modal parameters taken soon after installation of the platform are available. Under such circumstances, comparison of measured data for monitoring purpose can be based on the analytical results.

The experimental results presented confirmed all the observations of the analyses. While complete severance of the diagonals in the vertical plane and even a half-through crack in one of them produced measurable shifts in natural frequencies within the first or the second flexural mode, a complete severance of horizontal member 104 did not produce any detectable changes in any modal frequency because the member was highly redundant. It was also noted that severance of a member affected only those modes for which its presence was important, leaving the rest of the modes unaffected.

A change in the deck mass affected the natural frequency on the expected lines. Therefore all shifts in natural frequencies could not be attributed to structural damages unless a close watch was kept on the variations in deck mass. The conclusion of the analytical study that the changes in deck mass have a similar influence on all the modes could not be verified here because of the high frequencies of all modes above fundamental frequency. Nevertheless, all results confirmed the observation that the shift in natural frequencies alone could be used to identify the presence of structural damage only when the member involved was very important for stiffness of the structure.

TABLE 2—NATURAL FREQUENCIES OF THE MODEL FIXED IN WATER—COMPARISON OF RESULTS

Deck Mass (kg)	Condition of Model	FEM: I x-flexure (Hz)	FEM: II x-flexure (Hz)	Experimental: I x-flexure (Hz)	Experimental: II x-flexure (Hz)
10	No damage	4.91	13.91	4.25	11.55
10	86 missing	4.79 (−3.02)	13.87 (0)	4.1 (−3.5)	11.3 (−2.2)
10	114 missing	4.66 (−5.6)	10.62 (−23.6)	4.02 (−5.4)	8.5 (−26.4)
12	No damage	4.66 (−5.6)	13.78 (0)	3.95 (−7.1)	11.5 (0)
12	86 missing	4.52 (−8.5)	13.74 (0)	3.87 (−8.9)	11.2 (−3.0)
12	114 missing	4.42 (−10.5)	10.5 (−25.0)	3.79 (−11.0)	8.5 (−26.4)

Values in bracket indicate percent change.

Mode Shapes and Structural Damage

All of the mode shapes presented in Figs. 7–11 and 13–15 show good agreement between the analysis and experi-

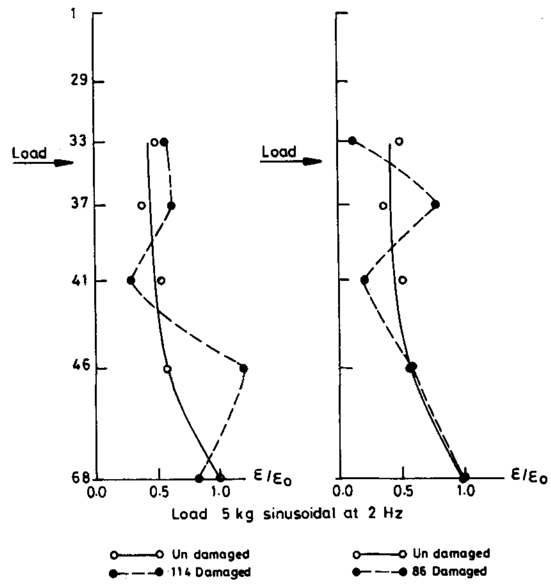

Fig. 12—Relative strains in the model (with respect to strain at fixed end of undamaged model ϵ_0)

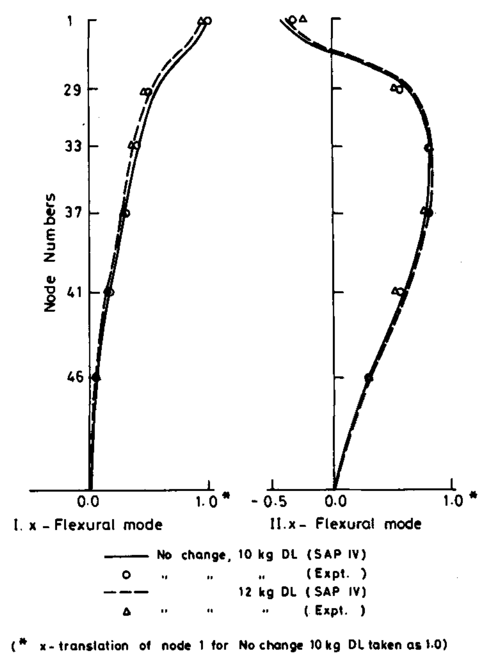

Fig. 13—Mode shapes, effect of deck load (model fixed in water)

ment, both when the model was fixed in air and in water. Figures 7 and 13 show the variation in mode shape due to changes in deck mass. As observed in the analytical studies, the deck-mass changes did not affect the basic form of the mode shapes. The second flexural mode of the model whose frequency was much higher than the fundamental also did not get affected by the change in deck mass except for a marginal change when the model was fixed in water.

Changes in mode shapes in the presence of structural damages in load-bearing bracings are presented in Figs. 8, 9, 10, 14 and 15. The influence of structural damages on mode shapes is clearly visible in all cases. Not only did they deviate from the basic form, but the magnitude of change depended on the severity of the damage in the structure. It was also seen that these shifts in mode shapes initiated very near the damage location. Even a half-through crack in one of the members produced measurable changes in mode shapes as can be seen in Fig. 8. Figures 11 and 15 show the combined effects of deck-mass changes and structural damage in the mode shape. It is very clear

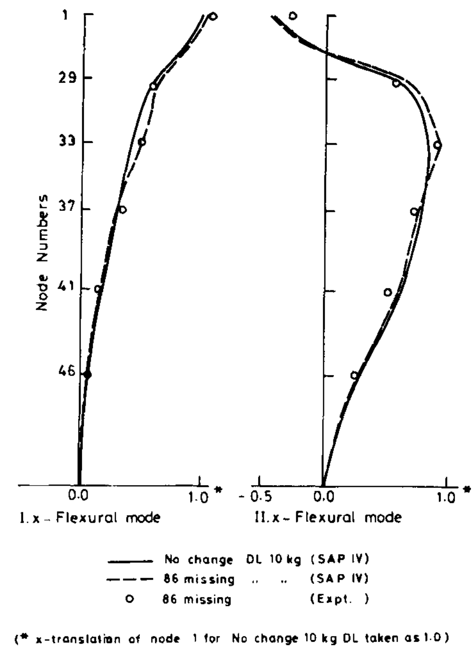

Fig. 14—Mode shapes, effect of damage (model fixed in water)

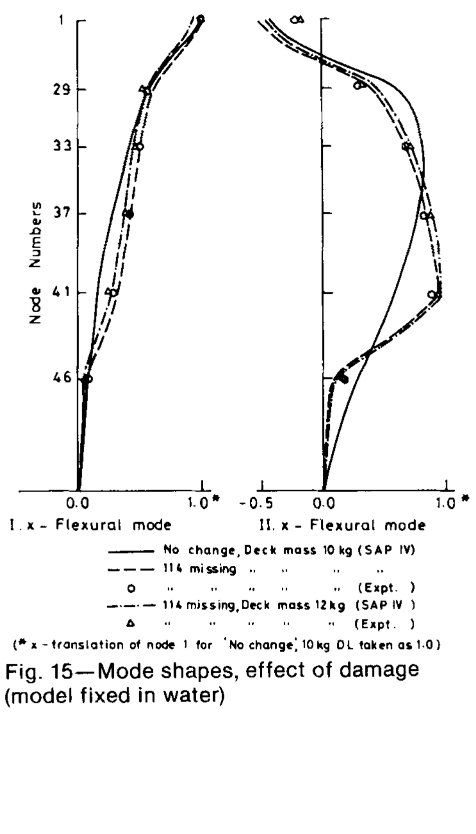

Fig. 15—Mode shapes, effect of damage (model fixed in water)

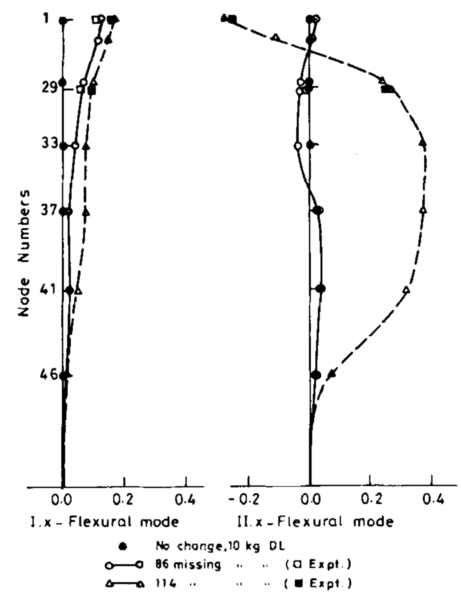

Fig. 16—y translation of flexural modes in x direction (x translation of node 1 for I mode taken as 1)

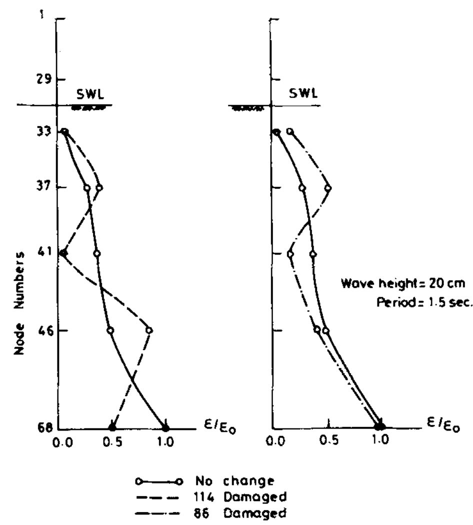

Fig. 17—Relative strains in the main leg (with respect strain at fixed end of undamaged model ϵ_0), model fixed in water

that the change in mass did not influence the shifts due to structural failure.

Wave loading of the model with periods ranging from 1.5 to 3 s and heights from 18 to 20 cm were sufficient to excite even the high-frequency second flexural mode of the model. This amply proved that ambient excitation was sufficient to excite a number of higher modes of the platform and sensitive accelerometers were adequate to acquire the required information on mode shapes.

Modal Vectors Perpendicular to Dominant Modal Direction and Structural Damage

Figure 16 and Tables 3 and 4 present these results. As can be seen, structural damages altered the dominant uniaxial mode shapes to diagonal ones. This resulted in larger modal vectors in the perpendicular direction.

The more severe the damage, the more pronounced was this effect. Experimental results confirmed this observation. These results are presented as the ratio of x to y translations in Tables 3 and 4. The usefulness of this information can be shown through an example. With half-through crack in member 114, the ratio dropped to 77.6 from 403. The complete severance of the same member brought this value to 9.4. As can be expected this effect was maximum in the affected node. These values presented in Table 4 for nodes above water are an important tool for monitoring purposes, if for any technical reasons underwater measurements are not feasible. Similar effects expected at higher modes for damages in redundant members could not be verified experimentally because of the low-frequency response of accelerometers used in the experiments.

Nodal Strains and Structural Damages

Measurements of nodal strains can also provide additional information apart from the already discussed points. Figures 12 and 17 show the strain distribution along one of the legs for damaged and undamaged conditions. Distribution is drawn as the ratios of maximum strain at the fixed end. It is evident that at the affected node, strain increased considerably. With the availability of highly reliable strain gages, especially of the vibrating wire type, strain measurement can provide very useful information on structural integrity along with the modal parameters.

A Scheme for Integrity Monitoring

Based on this investigation and also on the results already available, it can be seen that instrumented structural-integrity monitoring is viable, if the method is carefully applied and inferences are not limited to frequencies alone. A scheme is proposed below for integrity monitoring of fixed offshore platforms.

A detailed dynamic analysis of the complete platform must be the first step for any scheme. The model analyzed

TABLE 3—RATIOS OF MODAL VECTORS IN THE X AND Y DIRECTIONS FOR I AND II FLEXURAL MODES IN X DIRECTION—COMPARISON OF RESULTS

Mode	Node No.	No change FEM	No change Exp.	114 Half-through cut FEM	114 Half-through cut Exp.	114 missing FEM	114 missing Exp.	86 missing FEM	86 missing Exp.	145 missing FEM	145 missing Exp.
I Flexure X direction	1	403.04	385.68	77.58	86.91	9.36	7.38	8.34	8.78	232.5	256.90
	29	541.11	528.90	82.02	71.33	10.41	8.52	9.22	10.59	123.0	150.82
	33	39.67	51.76	118.07	105.24	11.13	9.78	12.76	13.88	91.25	98.53
	37	627.50	659.83	43.83	36.78	7.51	6.35	21.36	20.56	37.29	46.59
	41	7.56	5.85	11.54	10.50	12.74	14.61	9.85	7.38	12.33	14.55
	46	47.00	47.80	∞	18356.00	9.75	9.33	45.0	42.10	15.75	18.78
II Flexure X direction	1	81.33	75.52	13.72	12.53	3.02	2.98	11.86	10.53	22.00	25.03
	29	174.11	195.31	12.03	9.80	2.61	1.88	11.28	8.73	42.80	39.85
	33	75.68	85.66	12.09	11.88	2.84	2.57	16.86	15.88	345.60	402.85
	37	31.54	32.59	13.56	11.77	3.18	2.92	28.30	23.78	∞	14678.50
	41	10.18	9.80	29.43	30.53	3.94	3.24	8.40	6.53	320.25	356.80
	46	17.00	13.59	47.60	50.86	2.47	2.52	12.33	9.79	14.77	16.88

TABLE 4—RATIOS OF MODAL VECTORS IN THE X AND Y DIRECTIONS OF ABOVE-WATER NODES FOR DIFFERENT CONDITIONS

Mode No.	Node No.	No Change				86 missing				114 missing			
		FEM		Exp.		FEM		Exp.		FEM		Exp.	
	Deck Mass	10 kg	12 kg	10 kg	12 kg	10 kg	12 kg	10 kg	12 kg	10 kg	12 kg	10 kg	12 kg
I X-Flexure	1	192.9	216.2	209.7	221.3	8.3	8.46	8.4	8.9	6.04	6.6	5.9	6.26
	29	177.0	199.2	186.5	206.3	9.1	9.3	9.5	9.7	7.0	7.6	6.6	6.9
II X-Flexure	1	845.8	1851.9	∞	∞	22.2	20.9	18.9	18.9	2.0	2.1	1.7	2.0
	29	70.6	2460.5	75.9	∞	22.5	16.5	22.0	18.7	1.5	1.67	1.4	1.5

must be complete in all respects. As far as possible, a good estimate of the deck mass and the marine growth must be taken and represented in the analysis. A parametric study varying deck mass, marine growth, lateral restraints of piles computed from the soil data of the location, etc., must be done and kept as a data base. Results of these analyses, if available beforehand, will be handy for system identification when measurements are taken for the first time.

Natural frequencies as well as vectors in two perpendicular directions on diagonally opposite legs are the proposed measurements, initially, on the portion of the platform above still-water level. Acceleration response using very sensitive biaxial servoaccelerometers and autospectral analysis of the acceleration response are the proposed methods of data collection and analysis. Measurements on five to six points on each leg in both directions are necessary to identify the various modes and frequencies. Comparison of these results with those of the analyses will be the next stage. Comparison must be not only for frequencies but also for mode shapes with available data at different points in the legs and also for the translation perpendicular to the dominant modal direction. If a suitable analytical model can be identified and if there are large variations in certain modes or the modal vectors are drastically different at nodes in diagonally opposite legs, underwater measurements are advisable to determine mode shapes completely which can reveal structural defects. Alternatively, for the existing platforms, these measurements can be best done soon after a physical inspection by divers. Such a set of results would serve as a reference for all subsequent measurements.

New platforms to be installed have an advantage that some of the instruments necessary can be installed at the time of fabrication itself, thus avoiding the dependence on divers totally. Biaxial accelerometers can be installed at different nodal points on diagonally opposite legs. As far as the safety of these instruments is concerned, the ideal location would be the annular space between the pile and the main leg. This annular space after installation of the jacket will be grouted and that ensures the safety of the accelerometers from all environmental hazards. All the cable connections can also be laid through this space up to the deck where data-collection instruments can be located. In addition to the sensitive accelerometers for redundancy in measurements, strain gages of long gage lengths can be located at all nodes of diagonally opposite legs. Considering the permanence of the strain-gage installation, an ideal choice would be vibrating wire strain gages. On the whole for a platform like the one analyzed here, the number of biaxial accelerometers required would be 10 or 12 along with an equal number of strain gages.

One of the major advantages of this procedure is the availability of data from the day of installation of the jacket. All the required data for integrity monitoring can be collected whenever required and it would be a routine procedure to be repeated periodically.

The importance of the data collected from a platform under working conditions need not have to be emphasized. With additional information on wave height, current and wind, response of the platform for actual loading can be obtained and these data will be of extreme importance to economize future designs.

Conclusions

Based on the results obtained from the dynamic analyses of a well platform, a physical model study was carried out to verify the conclusions and to check the adequacy of the measurement techniques for collection of data. From the analyses and the model test, it is shown that structural-integrity monitoring based on dynamic response is a viable technique, provided the measurements are not restricted to deck for frequency shift alone. Though these conclusions are not based on actual field measurements on platforms, judging from the reported results, the present measurement technique is adequate to obtain modal parameters of the platform, namely natural frequencies and modal vectors in two perpendicular directions. It has been shown that the modal characteristics can reveal not only the presence of structural damages but also locate them without ambiguity. The sensitivity of modal vectors perpendicular to the predominant modal direction is clearly established not only for damages on load-bearing members but also for highly redundant members. Based on all these results, a scheme for integrity monitoring is suggested which can be used on existing platforms and platforms to be installed. It is advised that all the necessary devices be fixed beforehand during the fabrication stage itself.

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References

1. Bombassei, G. and Mazzon, M., "Structural Integrity Monitoring for Off-shore," Proc. Int. Symp. on Offshore Struct., COPPE, Brazil (Oct. 1979).
2. Bouwkamp and Shahrivar, F., "Damage Detection in Offshore Platforms Using Vibration Information," ASME Symp. on Offshore Mech/Arctic Eng., 174-185 (1984).
3. Coppolino, R.N. and Rubin, S., "Detectability of Structural Failures in Offshore Platforms by Ambient Vibration Monitoring," OTC 3865, 101-110 (1980).
4. Duggan, D.M., Wallace, E.R. and Cladwell, S.R., "Measured and Predicted Vibrational Behaviour of Gulf of Mexico Platforms," OTC 3864, 91-100 (1980).
5. Duggan, D.M., Wallace, E.R. and Cladwell, S.R., "Measured Vibrational Behaviour of Gulf of Mexico Platform," OTC 3137, 199-210 (1981).
6. Idichandy, V.G., "Integrity Monitoring of Fixed Offshore Platforms," PhD Diss., Indian Inst. of Tech., Madras, India (1986).
7. Idichandy, V.G., Ganapathy, C. and Srinivasa Rao, P., "Structural Integrity Monitoring of Fixed Offshore Platforms," invited paper, Rep. of the Int. Assoc. of Bridge and Struct. Eng. on Monitoring of Large Structures and Assessment of Their Safety (1987).
8. Kenley, R.M. and Dodds, C.J., "West Sole WE Platform: Detection of Damage by Structural Response Measurements," OTC 3866, 111-118 (1980).
9. Loland, O. and Dodds, C.J., "Experiences in Developing and Operating Integrity Monitoring Systems in the North Sea," OTC 2551, Houston (1976).
10. Nataraja Raj, "Structural Integrity Monitoring in Real Seas," OTC 4538, Houston, 221-228 (1983).
11. Rubin, S. and Coppolino, R.N., "Flexibility Monitoring of Offshore Jacket Platforms," OTC 4535, 201-208 (1983).
12. Vandiver, J.K., "Structural Evaluation of Fixed Offshore Platforms," PhD Diss., Mass. Instit. of Tech., Woods Hole Oceanographic Inst. (1975).
13. Vandiver, J.K., "Structural Damage Detection by Measurement of Dynamic Response," Spring Mtg. Soc. Naval Arch. and Marine Eng., San Francisco, 173-181 (1977).
14. Wojnarowski, M.E., Stiansen, S.G. and Reddy, N.E., "Structural Integrity Evaluation of a Fixed Platform Using Vibration Criteria," OTC 2909, Houston, 247-256 (1977).
15. Yang, J.C.S., Chue, J., Tsai, W.H. and Aggour, M.S., "Dynamic Characteristics and Response of Offshore Platform Scale Models on Pile Foundations," ASME Symp. on Offshore Mech/Arctic Eng., 89-95 (1983).