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Structural Integrity Monitoring of Fixed Offshore Platforms

Surveillance de la tenue structurale des plate-formes marines fixes

Gebrauchsfähigkeitüberwachung von festgesetzten Seeplattformen

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SUMMARY
This paper describes a comprehensive study on Structural Integrity Monitoring of Fixed Offshore Platforms based on their dynamic response. Analytical and experimental investigations have been carried out to identify factors in dynamic response most sensitive to structural damages, despite the presence of changes in parameters other than damages, affecting dynamic response. Based on this study, a scheme for integrity monitoring has been proposed which has the potential to replace, if not, at least reduce the frequency of the present uneconomical and hazardous diver inspection.

RESUME
Cet article decrit une étude de la surveillance de la tenue structurale des plate-formes marines fixes sur la base de leur réponse dynamique. Des recherches théoriques et expérimentales ont été effectuées en vue d'identifier les éléments de la réponse dynamique qui sont les plus sensible à des dommages structuraux. On en a déduit un plan de surveillance de la tenue pouvant remplacer, sinon au moins réduire la fréquence des dispendieuses et hasardeuses inspections sous-marines habituelles.

ZUSAMMENFASSUNG
Dieser Beitrag beschreibt ein Studium der Gebrauchsfähigkeit von festgesetzten Seeplattformen auf Grundlage deren dynamischen Antwort.
Analytische une experimentelle Forschungen wurden unternommen um die zu den Tragwerksschäden empfindlichten Elementen in der dynamischen Antwort zu bestimmen.
Von dieser Forschungen ist ein Überwachungschema abgeleitet worden, welches die kostspieligen und unsicheren gewöhnlichen Untersee-besichtingungen wenn nicht ersetzen, wenigstens deren Häufigkeit vermindern kann.

1. INTRODUCTION

Majority of the offshore oil production platforms belongs to the jacket type of fixed structure, a welded steel tubular space frame. These platforms and many more to be installed in future are designed for all types of environmental loads and for a useful life span of more than two decades. Such a long service in a very hostile environment prevailing in the ocean, makes it necessary to inspect these structures for identifying and locating possible structural defects for timely maintenance and repair.

At present, all over the world trained divers are being utilized for this inspection. But, poor visibility, concealment of damages by excessive marine growth, non-availability of trained divers, prohibitive cost and dependence of diver inspection on weather conditions, limit the viability of this hazardous operation both technically and economically. Consequently, a need has been felt to develop better techniques, preferably operated from the deck of the platform to monitor the structural integrity of the installation periodically and an instrumented integrity monitoring based on dynamic response was proposed by many researchers as the best alternative.

1.1 Integrity monitoring based on dynamic response

Structural integrity monitoring based on dynamic response is not new to civil engineers, as this method has been made use for land-based structures after seismic activity or fire hazards. The method itself is based on the fact that any structure, regardless of the type, has natural modes of vibration which are fundamental characteristics of the structure and do not change unless there are changes in its 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 reveal the integrity of the structure.

Thus it appears that integrity monitoring reduces to determination of modal parameters of the structure. However, it should be kept in mind that there are certain other factors apart from structural damages e.g. variation in mass distribution that could possibly alter the modal characteristics and this can lead to serious difficulties including erroneous conclusions while interpreting the measured data. Based on investigations by some organisations on simple theoretical and physical models, different approaches had been suggested to overcome this difficulty.

1.2 Background information

Organisations involved in the research of this topic are certification agencies, research establishments on behalf of offshore oil industry as well as universities. Some of the important among them are American Bureau of Shipping, Lloyds Register of Shipping, Det Norske Veritas, Norske Agip and Technomare, Structural Monitoring Ltd., Keith Feibush Associates, Aerospace Corproation, GKSS Forschungs Zentrum, Institute Francais du Petrole, The Massachusetts Institute of Technology, University of Maryland and University of California.

These investigators used analytical and physical models for their work and many of them also took measurements on actual production platforms. Apart from the global frequency monitoring, some authors suggested changes in mode shapes as well as shift in modal vectors in all six degrees of freedom of different modes and these organisations are: The Aerospace Corporation [1,2] and the University of Maryland [3]. However, both these organisations based their conclusions on very simple analytical and physical models and suggested further detailed work including analysis using 3-D finite element model of actual platforms to fully understand and develop the potential of the method as a tool for structural integrity monitoring.

1.3 Scope of present work

As a result of these suggestions, it was felt that there was a need for study all the aspects of integrity monitoring, incorporating every factor influencing the dynamic response of the structure with the help of a 3-D finite element model and to prove the results obtained in the laboratory with the help of a physical model. Consequently the present work is executed in the following sequence.

Formulate a 3-dimensional FE model of an existing well platform consisting of the full deck structure, distributed deck mass, jacket, grouted piles, launch truss, marine growth, hydrodynamic added mass, effect of pile foundation etc., for dynamic analysis using structural analysis package SAP IV, so as to determine the modal parameters like natural frequencies and mode shapes for various conditions of the factors influencing the dynamic response of the platforms. Based on the results of the analysis, test a physical model of the platform under different types of excitation to study the efficiency of the measuring system in identifying the modal parameters and to prove the results of the analysis. Finally, to propose a scheme for integrity monitoring based on the results of these investigations[4].

2. ANALYTICAL INVESTIGATION

2.1 Features of the platform

The well platform selected for analysis consisted of a jacket, deck with machinery and had four main piles and an equal number of skirt piles. The outer diameter of each leg was 1.335 m and wall thickness 0.020 m. Two of the main legs had a batter of one in eight in two perpendicular directions and the other two had the same batter only in one direction. A key plan of the jacket is shown in Fig.2.

On the deck of the platform were located a crane, helideck, test separator, fuel storage tank, generators and other essential machineries. The total deck load inclusive of the live load was 503 t.

All the eight piles were steel tubulars of external diameter 1.220 m with a wall thickness of 0.025 m and these were driven through the legs to a depth of 72 m below mud level. The annular space between the leg and the pile was grouted with cement.

This platform was situated in a water depth of 85 m. The overall height from mud-level to the top of the deck was 107 m.

2.2 Formulation of the FE Model

In the FE model all the members were idealised as 3-D beam elements having all six degrees of freedom. Nodes were located at the centroidal axes of the intersecting members. Figs.1 and 2 show the vertical framing, launch trusses, horizontal framings and other deck frames. As can be seen, almost the entire structure was represented in the mathematical model and only a very few unimportant members at horizontal levels were left out.

Additional mass due to equipments on the deck, grout in the pile-leg annular space, water inside the pile etc. were included in the model as lumped masses in the respectives nodes.

The effect of the entrained water or added mass was included as lumped mass in the model as the mass of the water displaced by the submerged members. Depending on the orientation of the member the mass was lumped by resolution of vectors in the respective directions.

The soil-pile interaction and their lateral restraints were adequately represented by linear spring whose stiffness was worked out based on the slope of the load deflection curves. These springs were treated as boundary elements in the analysis.

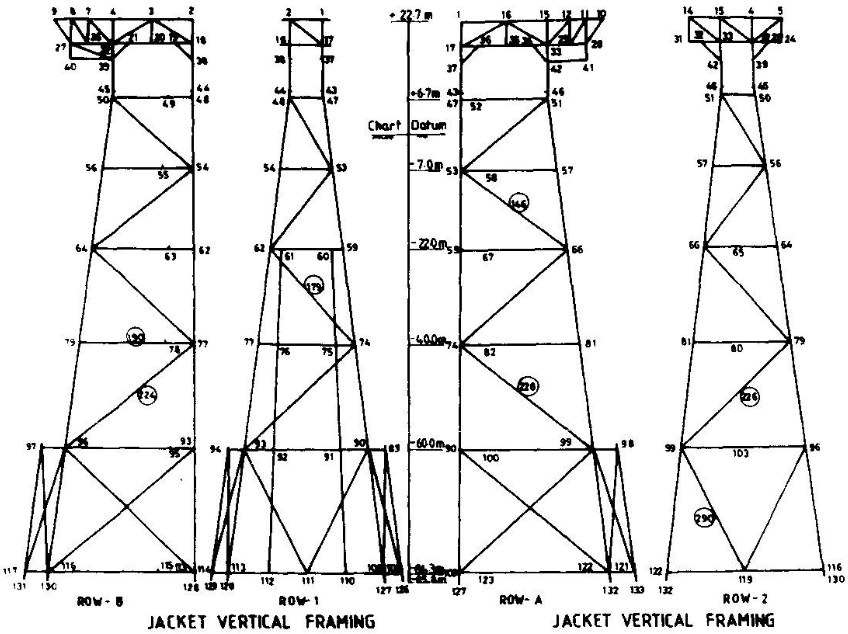

+22.7m
+6.7m
Chart Datum
-7.0m
-22.0m
-40.0m
-60.0m
ROW - B
ROW - 1
ROW - A
ROW - 2
JACKET VERTICAL FRAMING
JACKET VERTICAL FRAMING

Fig.1

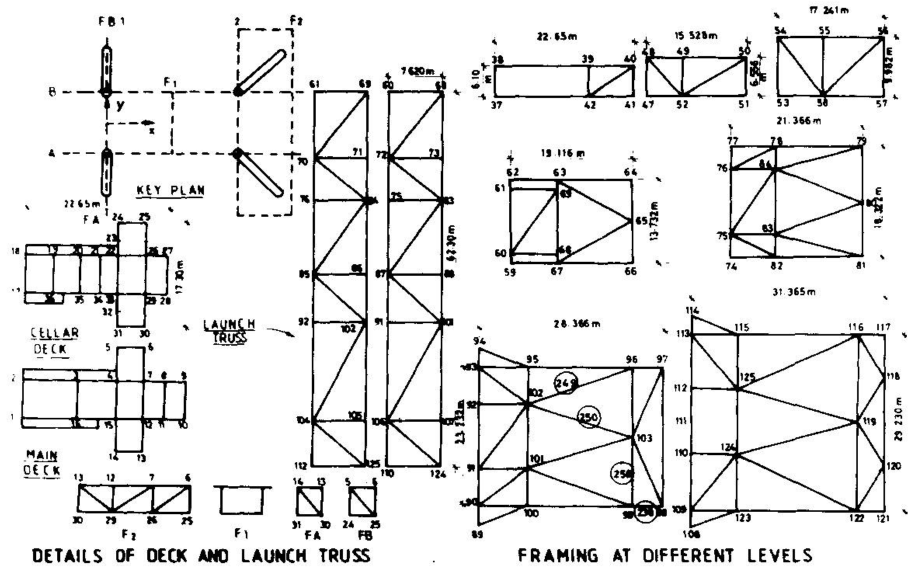

KEY PLAN
CELLAR DECK
MAIN DECK
LAUNCH TRUSS
DETAILS OF DECK AND LAUNCH TRUSS
FRAMING AT DIFFERENT LEVELS

Fig.2

A build up of marine growth on any structure produces an increase in mass without any significant change in stiffness. This causes a reduction in natural frequency. Additionally an increase in geometric dimension due to marine growth results in corresponding increase in added mass. As an excessive marine growth could be expected in tropical waters, marine growth distribution as given in CIRIA report [5] was assumed. This assumes for example a growth of 0.300 m at the interface. Effect of this additional mass was included in the model as lumped mass and added mass arising from the changed dimension in all cases of analysis of platform with marine growth.

2.3 Final model and details of computation

The final model used for the analysis had 253 nodes, 373 beam elements, 88 boundary elements representing lateral restraints of the piles, 24 different sections, lumped mass data representing deck mass and added mass of submerged members. Structural Analysis Program SAP IV was utilized for dynamic analysis of this problem.

Total number of linear simultaneous equations to be solved for the eigenvalue problem was 990 and the CPU time required for the solution of 10 eigenvalues was 20 min. and 12.5 min. for 5 eigenvalues on an IBM 370. This naturally involved a lot of computer time and hence majority of the problem analysed was for 5 eigenvalues.

2.4 Parametric study

Dynamic response and modal parameters of an offshore platform are dependent on different factors. From the reported results of a detailed study by ABS [6], the following parameters were identified for parametric study.

i) Deck mass, a change of ± 5 and $\pm$ 10 percent.

ii) Foundation change in top layer springs to simulate scour or soil build up. A combination of scour and build up at different legs was also considered.

iii) Marine growth, an excessive growth is assumed as expected in tropical waters.

iv) Damage in members, complete severance were simulated by reducing all sectional properties to a value 10^{-15}, thus making it ineffective. Simulation of a half-through-cut in a member was achieved by modifying sectional properties to those of a semicircular open section.

In the analysis, initially, the basic structure with 'NO CHANGE' in any of the parameters was analysed. To estimate the individual effects of parameters listed above they were varied and analysis carried out. Finally combined effect of all these parameters including damages in members were analysed in order to identify characteristics which could be used for monitoring structural integrity. Members damaged in the analyses were selected depending on its location as well as redundancy.

2.5 Results and Discussions

The results obtained in each analysis were natural frequencies, for different modes and modal vectors in all the 6 degrees of freedom representing the shapes of each mode. Because of certain limitations a few important results alone are presented here. These results presented here are representative and explain the general behaviour and the trend.

The following results are presented.

Change in natural frequencies for different conditions including structural damages in Tables 1, 2 and 3.

Translation perpendicular to the predominant modal direction for various cases in Tables 4, 5 and 6.

Ratios of modal vectors in two perpendicular direction in Table 7.

Changes in mode shapes in Figs.3,4,5,6,7,8,9 and 10.

2.5.1 Natural frequency and structural damage

There are a few important conclusions that could be derived from the results in Tables 1, 2 and 3. Missing diagonal members which are shear connectors change the natural frequencies of the platform depending on their location and their contribution to the overall stiffness of the structure, e.g. a missing member 224 introduces a change of 2.7 percent in the II mode whereas a missing 290 or even a half through cut in 290, the change is 15.4 in the IV mode. Another striking feature is the nonuniformity in the change in natural frequencies unlike in the case of a change that affects the structure as a whole, e.g. marine growth or a change in deck mass. For instance, a complete severance of a very important diagonal member 290 does not affect the frequencies of modes II, VIII and IX whereas the change is 15.4 percent for the IV mode. In other words a missing member changes the modal characteristics of those modes for which it is of importance. As expected severance of horizontal level members which do not substantially contribute to the lateral stiffness of the structure, had no effect on the natural frequencies. This is illustrated by the results for missing members 190, 250, 258 and 249. When combined situations are considered, an excessive marine growth masks completely the marginal changes in frequencies even due to complete severance of important members. However, the non-uniformity of changes in different modes are still maintained. Thus integrity monitoring based on frequecy shift alone, becomes impractical on platforms where there are excessive marine growth unless the severed member is very important like member 290 when the change in frequency in the IV mode is considerably larger than the rest.

2.5.2 Mode shapes for various situations

Results presented in Figs.3 to 10 show changes in mode shapes for different situations for the most affected main leg. Change in deck mass, scour or soil build up do not change the mode shape considerably and what is more important is that the basic form of the mode is maintained with very minor changes, while an excessive marine growth shifts the modes to a large extend despite the retention of the basic shape of the mode. All these indicate that these changes are general to the structure and affects the overall dynamic behaviour. This is in sharp contrast to the changes in mode shapes where damages are present. The results presented are mainly for load bearing members. No drastic change in predominant mode shape was expected with failure in redundant members. The table below shows a comparitive study of change in the mode shape vector in the predominant modal direction for the most affected mode for certain missing members.

Member	Node No.	Percent change	
		I Flexural mode	II Flexural mode
146	57	9.9	4.9
179	62	6.5	17.4
224	77	9.6	86.1
226	81	53.5	99.2
228	81	22.3	54.2
290	99	99.8	99.0

Description	Frequencies in Hz for Mode No									
	I	II	III	IV	V	VI	VII	VIII	IX	X
No change	0.5597	0.6131	0.8304	1.119	1.245	1.332	1.485	1.655	1.751	2.068
Deck Mass + 5 percent	0.5465 (-2.4)	0.6049 (-1.3)	0.8175 (-1.6)	1.106 (-1.2)	1.229 (-1.3)					
Deck Mass + 10 percent	0.5367 (-4.1)	0.5971 (-2.6)	0.8063 (-2.9)	1.095 (-2.2)	1.213 (-2.6)					
Marine Growth	0.5105 (-8.8)	0.5189 (15.4)	0.7193 (-13.4)	1.003 (-10.4)	1.094 (-12.1)					
2 m scour on all legs	0.5584 (-0.23)	0.6082 (-0.08)	0.8249 (-0.7)	1.101 (-1.6)	1.224 (-1.7)	1.228 (-3.3)	1.472 (-0.9)	1.619 (-2.2)	1.749 (-0.6)	2.046 (-1.1)
Marine growth &+5 per cent DM	0.5026 (-10.2)	0.5137 (-16.21)	0.7101 (-14.5)	0.9880 (-11.7)	1.091 (-12.4)					
Marine growth & 2 m scour	0.5070 (-9.4)	0.5149 (-16.0)	0.7115 (-14.3)	0.9897 (-11.6)	1.059 (-14.9)					
Marine growth, 2 m scour & +5 percent deck mass	0.5001 (-10.7)	0.5091 (-17.0)	0.7026 (-15.4)	0.9752 (-12.9)	1.056 (-15.2)					
Marine growth & Diff. support	0.5098 (-8.9)	0.5182 (-15.5)	0.7223 (-13.0)	1.007 (-10.0)	1.077 (13.5)					

TABLE 1 Change in natural frequencies for changes other than damages

Values in bracket give percent change

Description	Frequencies in Hz for Mode No.									
	I	II	III	IV	V	VI	VII	VIII	IX	X
No change	0.5597	0.6131	0.8304	1.119	1.245	1.332	1.485	1.655	1.751	2.068
Missing member 179	0.5596 (0)	0.6131 (0)	0.7938 (-4.4)	1.100 (-1.7)	1.245 (0)					
Missing member 224	0.5459 (-2.5)	0.5963 (-2.7)	0.8293 (-0.1)	1.100 (-1.7)	1.222 (-1.9)	1.319 (-1.0)	1.485 (0)	1.653 (-0.1)	1.746 (-0.3)	2.036 (-1.6)
Missing member 228	0.5516 (-1.5)	0.5904 (-3.7)	0.8223 (-1.0)	1.119 (0)	1.218 (-2.2)	1.314 (-1.35)	1.485 (0)	1.655 (0)	1.746 (-0.3)	2.040 (-1.4)
Half through out in 290	0.5438 (-2.8)	0.6124 (-0.1)	0.7949 (-4.3)	0.9467 (-15.4)	1.195 (-4.0)					
Missing member 290	0.5438 (-2.8)	0.6124 (-0.1)	0.7944 (-4.3)	0.9463 (-15.4)	1.188 (-4.6)	1.260 (-5.4)	1.481 (-0.3)	1.655 (0)	1.751 (0)	2.040 (-1.4)
Missing member 190	0.5597 (0)	0.6131 (0)	0.8304 (0)	1.119 (0)	1.245 (0)					
Missing member 250	0.5594 (0)	0.6131 (0)	0.8304 (0)	1.119 (0)	1.245 (0)	1.332 (0)	1.484 (0)	1.655 (0)	1.750 (0)	2.067 (0)
Missing member 258	0.5587 (0)	0.6131 (0)	0.8300 (0)	1.118 (0)	1.245 (0)	1.332 (0)	1.484 (0)	1.655 (0)	1.750 (0)	1.990 (0)
Missing member 249	0.5594 (0)	0.6131 (0)	0.8304 (0)	1.119 (0)	1.245 (0)	1.332 (0)	1.485 (0)	1.655 (0)	1.750 (0)	2.067 (0)

TABLE 2 Change in natural frequencies and structural damages
Values in bracket give percent change

Description	Frequencies in Hz for Mode No.									
	I	II	III	IV	V	VI	VII	VIII	IX	X
No change	0.5597	0.6131	0.8304	1.119	1.245	1.332	1.485	1.655	1.751	2.068
Half through out in 290 & Deck mass + 5%	0.5322 (-4.9)	0.6131 (0)	0.7860 (-5.4)	0.9341 (-16.5)	1.185 (-4.8)					
Marine growth & missing member 290	0.4829 (-13.7)	0.5163 (-15.8)	0.6967 (-16.1)	0.8493 (-24.1)	1.011 (-18.8)					
-do- & Deck mass + 5%	0.4766 (-14.9)	0.5121 (-16.5)	0.6866 (-17.3)	0.8421 (-24.8)	1.000 (-19.7)					
Marine growth, scour and missing member 290	0.4793 (-14.36)	0.5108 (-16.7)	0.6902 (-16.9)	0.8355 (-25.3)	0.9931 (-20.2)					
Marine growth, soil buildup & missing member 290	0.4853 (-13.3)	0.5200 (-15.2)	0.7010 (-15.6)	0.8585 (-23.3)	1.025 (-17.7)					
Missing member 228 & Deck mass + 10 percent	0.5290 (-5.5)	0.5757 (-6.1)	0.7591 (-8.6)	1.096 (-2.1)	1.186 (-4.7)	1.307 (-1.9)	1.436 (-3.3)	1.613 (-2.5)	1.671 (-4.6)	1.990 (-3.8)
Missing member 228, marine growth & soil buildup	0.4888 (-12.7)	0.5126 (-16.4)	0.7076 (-14.8)	1.011 (-9.7)	1.072 (-13.9)					
Missing member 228, marine growth & deck mass +5%	0.4818 (-13.9)	0.5028 (-18.0)	0.6947 (-16.3)	0.9874 (-11.8)	1.051 (-15.6)					

TABLE 3 Change in natural frequencies for combined situation
Values in bracket give percent change.

Node No.	Missing member			
	Nil	146	224	228
15	-0.085	2.59	2.35	2.81
33	-0.19	2.62	2.17	2.82
42	-0.206	2.55	2.04	2.71
46	0.287	1.89	2.26	1.99
51	0.369	1.80	2.28	1.87
57	0.353	1.71	2.00	1.71
66	0.170	0.76	1.58	1.76
81	0.087	0.53	1.09	1.61
99	-0.087	0.47	0.50	0.57
122	0.093	0.28	0.16	0.32
132	-0.050	0.14	0.07	0.16

TABLE 4 x-Translations of first flexural mode in y direction for different conditions

Node No.	Missing member			
	Nil	146	224	228
15	2.043	-0.31	4.636	-0.91
33	1.872	-0.22	4.259	-0.85
42	1.645	-0.29	3.731	-0.73
46	1.262	-0.19	2.802	-0.49
51	1.201	-0.18	2.647	-0.45
57	0.978	-0.16	2.043	-0.25
66	0.749	-0.29	1.501	-0.13
81	0.636	-0.21	1.138	0.04
99	0.377	-0.21	0.817	-0.17
122	0.121	-0.08	0.300	-0.09
132	0.049	-0.03	0.124	-0.04

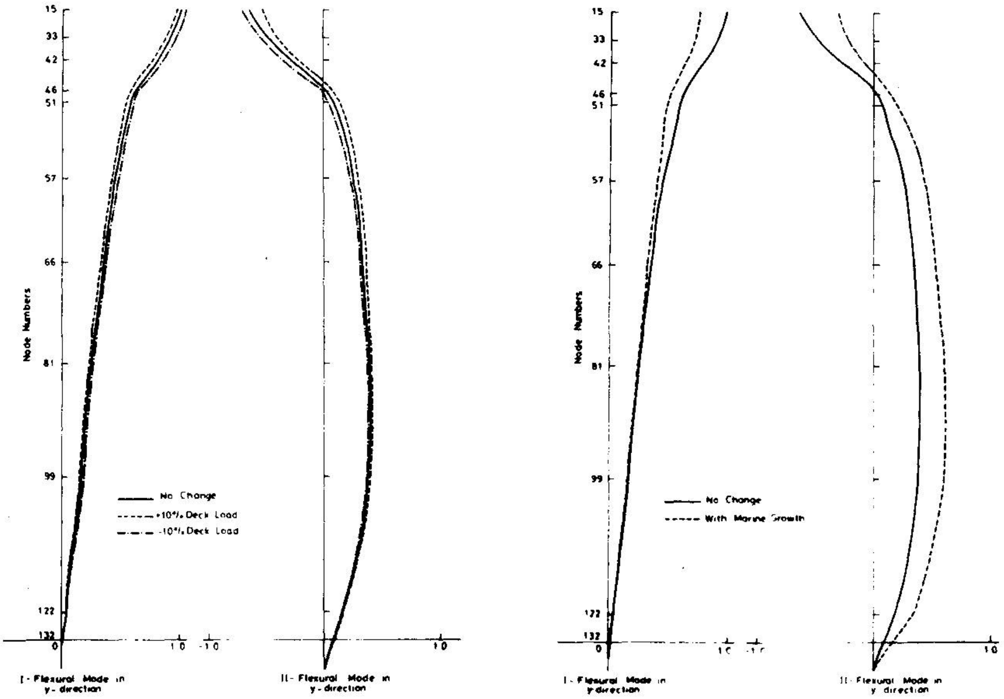
TABLE 5 x-Translations of first flexural mode in y-direction for different conditions

Node No.	No change	Deck mass +10%	Marine Growth	Missing member 228	Deck mass 10% and missing member 228	Marine growth, deck mass +10% & missing member 228
15	-0.085	-0.25	3.60	2.81	2.394	2.21
33	-0.190	-0.34	3.38	2.82	2.416	2.04
42	-0.206	-0.35	3.18	2.71	2.238	1.91
46	0.287	0.15	3.11	1.99	1.653	2.01
51	0.369	0.24	3.09	1.87	1.540	2.02
57	0.353	0.24	2.66	1.71	1.414	1.750
66	0.170	0.08	2.12	1.76	1.496	1.362
81	0.087	0.03	1.53	1.61	1.384	0.972
99	-0.087	-0.12	0.87	0.57	0.469	0.503
122	0.093	-0.11	0.42	0.32	0.268	0.239
132	-0.05	-0.05	0.20	0.16	0.136	0.112

TABLE 6 X-Translation of first flexural mode in Y-direction

Node No	No change			Missing member 250		
	x	y	y/x	x	y	y/x
4	3.75	7.5	2.0	3.75	7.53	2.01
22	3.13	5.86	1.87	3.11	5.89	1.89
39	2.18	3.51	1.61	2.18	3.53	1.62
45	0.16	-0.06	-0.37	0.15	0.09	0.60
50	-0.17	-0.40	2.35	-0.18	-0.38	2.11
56	-0.17	-0.98	5.76	-0.19	-0.96	5.05
64	0.32	-0.76	2.37	0.29	-0.74	2.55
79	0.75	-0.45	0.60	0.71	-0.44	0.62
96	0.89	-0.72	0.81	0.84	0.35	0.41
116	0.78	0.04	0.06	0.73	0.13	0.179
130	0.39	0.07	0.173	0.37	0.07	0.19

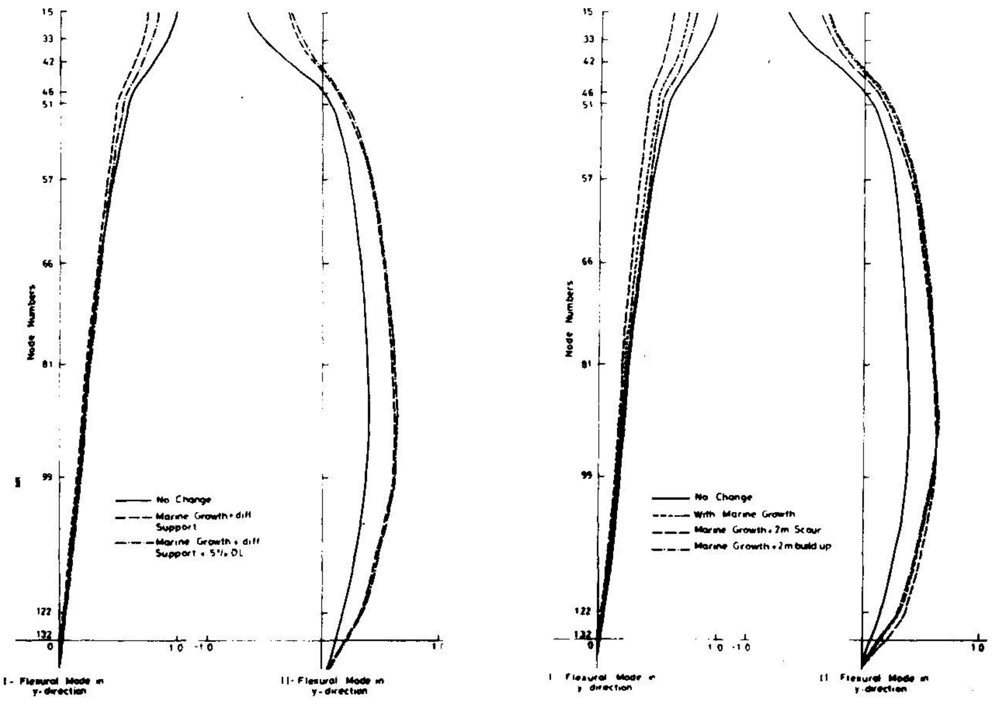
TABLE 7 Ratio of y to x-Translation of X mode for missing member 250



EFFECT OF DECK MASS VARIATION ON MODE SHAPES (Normalised wrt y-translation in Mode-1 of Node-15)

EFFECT OF MARINE GROWTH ON MODE SHAPES (Normalised wrt y-translation in Mode-1 of Node-15)

Fig.3



EFFECT OF MARINE GROWTH, DIFFERENTIAL SUPPORT AND DECK LOAD ON MODE SHAPES (Normalised wrt y-translation in Mode-1 of Node-15)

EFFECT OF MARINE GROWTH, SCOUR AND SOIL BUILD UP ON MODE SHAPE (Normalised wrt y-translation in Mode 1 of Node-15)

Fig.4

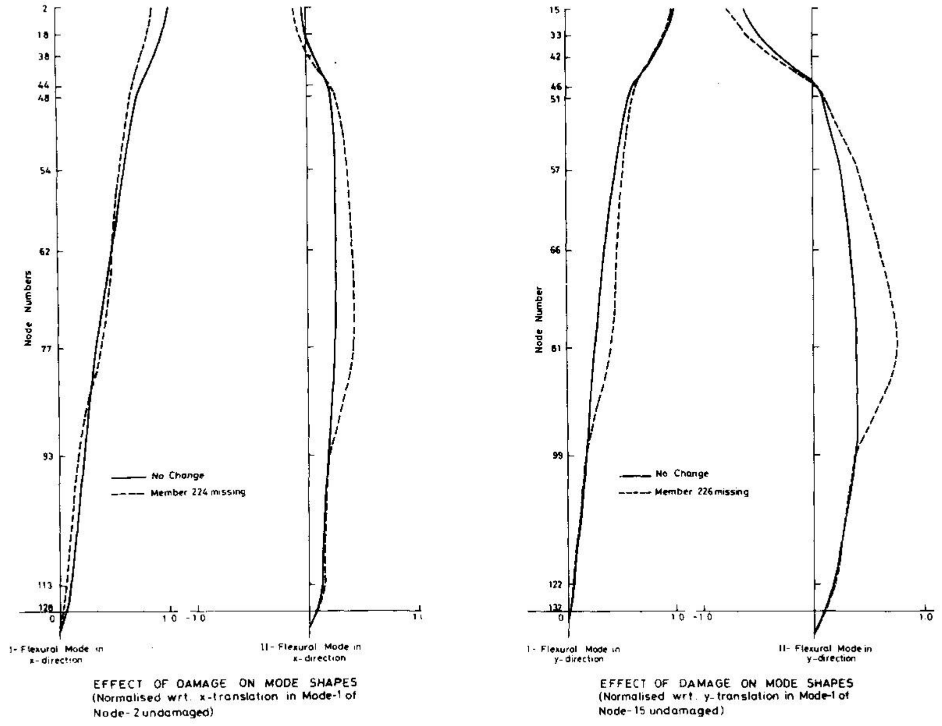

Node Numbers
No Change
Member 224 missing
I- Flexural Mode in x-direction
II- Flexural Mode in x-direction
EFFECT OF DAMAGE ON MODE SHAPES
(Normalised wrt. x-translation in Mode-I of Node-2 undamaged)
Node Number
No Change
Member 226 missing
I- Flexural Mode in y-direction
II- Flexural Mode in y-direction
EFFECT OF DAMAGE ON MODE SHAPES
(Normalised wrt. y-translation in Mode-I of Node-15 undamaged)

Fig.5

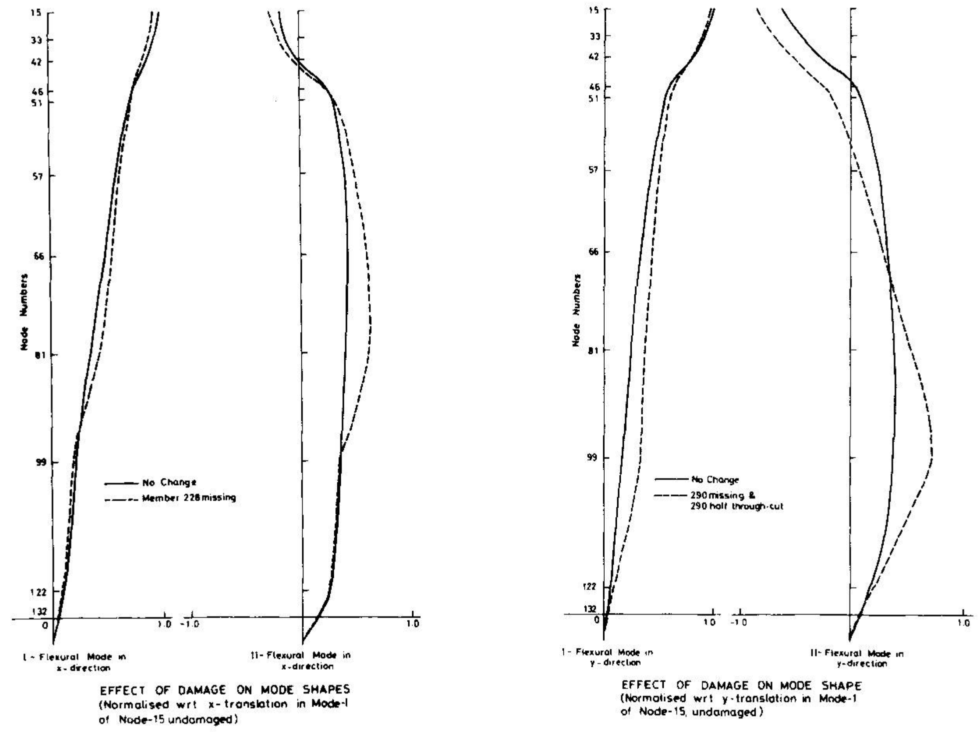
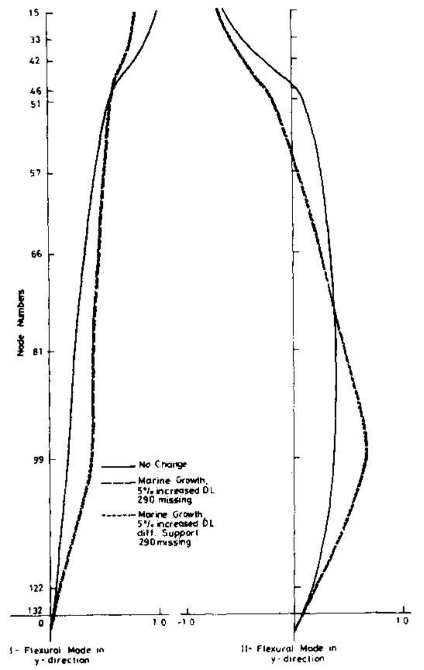
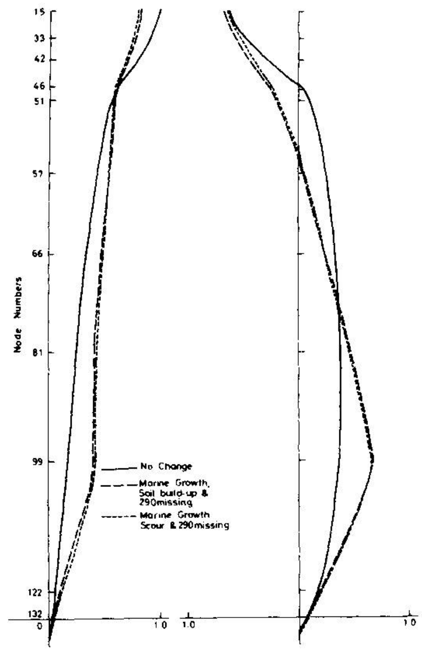

Node Numbers
No Change
Member 228 missing
I- Flexural Mode in x-direction
II- Flexural Mode in x-direction
EFFECT OF DAMAGE ON MODE SHAPES
(Normalised wrt x-translation in Mode-I of Node-15 undamaged)
Node Numbers
No Change
290 missing & 290 half through-cut
I- Flexural Mode in y-direction
II- Flexural Mode in y-direction
EFFECT OF DAMAGE ON MODE SHAPE
(Normalised wrt y-translation in Mode-I of Node-15 undamaged)

Fig.6



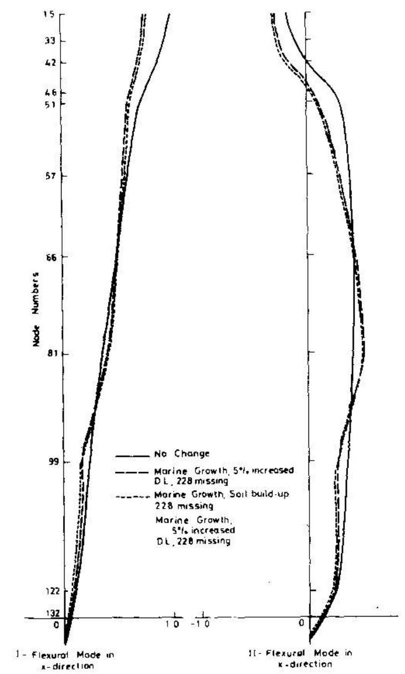
COMBINED EFFECT OF MARINE GROWTH, DIFFERENTIAL SOIL SUPPORTS, INCREASED DECK LOAD ON MODE SHAPES (Normalised w r t y-translation in Mode-1 of Node-15,undamaged

Fig.7



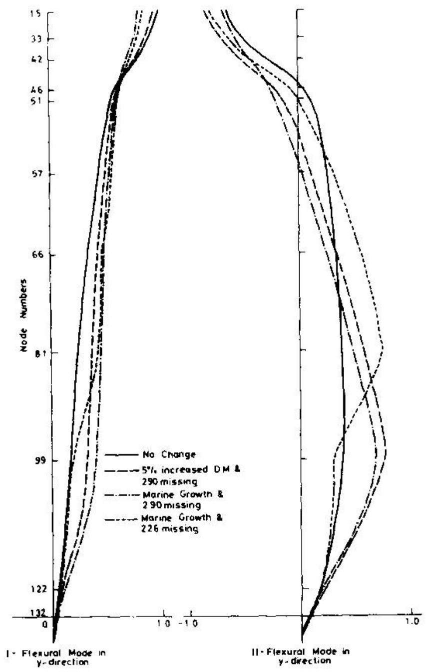
COMBINED EFFECT OF MARINE GROWTH, SOIL BUILD-UP, SCOUR AND DAMAGE ON MODE SHAPES (Normalised wrt y-translation in Mode-1 of Node-15, undamaged)

Fig.8



COMBINED EFFECT OF MARINE GROWTH, PILE SPRING, DECK LOAD, SOIL BUILD-UP & DAMAGE ON MODE SHAPES (Normalised w r t x-translation in Mode 1 of Node 15, undamaged)

Fig.9



COMBINED EFFECT OF CHANGE IN DECK LOAD, DAMAGE AND MARINE GROWTH ON MODE SHAPES (Normalised wrt y-translation in Mode-1 of Node-15undamaged)

Fig.10

The failure of 146 and 179 does not change the mode shape drastically because 146 is located close to the free end of the structure and 179 though located at the third level has two additional members close by belonging to the launch truss making it redundant.

The figures giving the combined effect of different situation on mode shape clearly indicate that they are more or less same as if the damage alone were present. Thus changes in any of the parameter were taken together with damages in members, the mode shapes remain unaltered and are same as though damages alone were present. Or in other words, changes in mode shape due to damages cannot be masked by changes in any other parameter affecting dynamic response.

2.5.3 Change in modal vector perpendicular to predominant modal direction

In the search for factors that are maximum affected by damages in members, it has been found that modal vector perpendicular to the predominant modal direction is a very sensitive factor which can be of use in monitoring. Tables 4-7 present these results. The tables are self explanatory. The changes are very drastic; in one case it is almost 33 times the value for undamaged situation. Even when there are changes in other parameters this translation remains to be very much different from the no change situation.

It is also seen that these results can provide clues for the condition of highly redundant horizontal level members. One typical result alone is presented here. The ratios of x to y translation of X mode are presented for nodes in one of the legs for missing member 250. The value of this ratio changes from 0.81 to 0.41 and 0.06 to 0.179 for the most affected nodes. It may be noted that these changes are seen only at higher modes and hence the real significance of this effect will depend very much on the capability of the measuring system to measure the translations at higher modes. If the results of measurements already reported are any indication, this must be possible with the usual methods of measurements.

3. EXPERIMENTAL INVESTIGATION

Experimental investigations were found necessary to verify the observations of the analyses as well as to prove the measurement procedure to be adopted to obtain the required information. For this limited objective, tests on a geometrically similar model, an analysis of the same with SAP IV and a comparison of both the results obtained would be sufficient. Moreover, it is almost impossible to design and test an elastic model of a jacket with available material and testing methods. The linear scale of the model was decided to be 1:35 based on the 2.5 m depth of water in the flume available. The model was made out of PVC tubes and the fundamental period of the model with deck load was nearly 4 Hz when fixed in water.

3.1 Test program

Though the model was planned to be tested in a flume under wave loading, considering the water depth in the flume and the difficulties in simulating damages in members as well as joining them back 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 to carry out the tests involving damages in more members in air by exciting the model with an electrodynamic excitor. In this case, any way, the results necessary were not dependent on the nature of excitation. As a result, tests were conducted for 5 damage situations in air and for 2 in the wave flume. In both these tests, the deck mass alone was varied because in the analysis, it was very clear that change in mass either in the deck or distributed on the structure was contributing maximum to the uncertainity in interpreting the data.

The physical model was excited with the help of an electrodynamic excitor. 6 accelerometers were used to measure the response at all the nodes of one of the main legs. 5 strain gauges were also fixed at these nodes. Accelerometer output was analysed in frequency domain with the help of FFT analyser to get the autopower spectrum of the response and the strain gauge data wasrecorded on a strip chart recorder. Results obtained were natural frequencies and amplitudes from FFT analyses and strains at the nodes. Experiments were also conducted in a flume under wave loading. Two views of the experimental set-up are shown in Figs.11 and 12.

3.2 Dynamic Analysis of the Model

As in the case of the well platform a finite element equivalent of the physical model was formulated for dynamic analysis using SAP IV. The principles governing the modelling was exactly same as those for the well platform. There were 74 nodes and 170 beam elements for the model which was assumed to be fixed at eight points, representing the four main legs and four skirt legs. Damages were simulated in the same way as in the case of the well platform. Figs. 13 and 14 show the FE model of the Physical model.

3.3 Results and discussions

The results obtained in the analysis and the experiments are presented in Tables 8, 9 and 10 and Figs.15 to 22 for various cases. The informations on frequencies as well as mode shape vectors clearly indicate the close agreement between the analytical and experimental results. Though there are differences in the exact magnitude of the frequency values by around 10 percent, the shift dueto damage in members are in good agreement. Strains in members were however, not obtained analytically and as a result, only results of measurements alone are presented. For the limited objectives already explained in the beginning of the chapter, the experimental results validate the behaviour predicted by analysis and also proves the adequacy of measurements for determining the required informations.

4. A SCHEME FOR INTEGRITY MONITORING OF FIXED OFFSHORE PLATFORMS

The results of the analytical and experimental investigation clearly indicate that Integrity Monitoring based on dynamic response can be viable, if it is carried out with a lot of care at every stage. Though it is desirable to restrict the measurements to deck alone, the results show that mode shape information which involves under water measurements will be necessary not only to establish the integrity but to locate the damages, if any, as it is evident from the figures that the mode shape deviates from the original near the vicinity of the damage. The scheme proposed below for integrity monitoring has obviously two stages, viz., analytical as well as field measurements on platform.

4.1 Analysis of the platform

A detailed three dimensional analysis of the platform is naturally the first step in this operation and this should be available before any measurements are taken. For the purpose of the analysis, a well proven general purpose structural analysis program can be made use of. As far as possible, complete structural and all hydrodynamic aspects of a partially submerged structure should be represented in the analytical model. The representation of the lateral restraints of pile should be based on the soil investigation data of the site. Once the model is ready, a parametric study can be carried out and the results of this study would later prove useful when actual measurements are undertaken. Natural frequencies, mode shapes of at least 10 modes and informations on modal vectors in all six degrees of freedom for all the modes are the results required at the end of this first stage of integrity monitoring.

4.2 Measurements on platform

Recording of acceleration response simultaneously at diagonally opposite legs and spectral analysis of this data forms the next stage. Biaxial accelerometers are advisable, as it was seen in analysis that the data of translation perpendicular

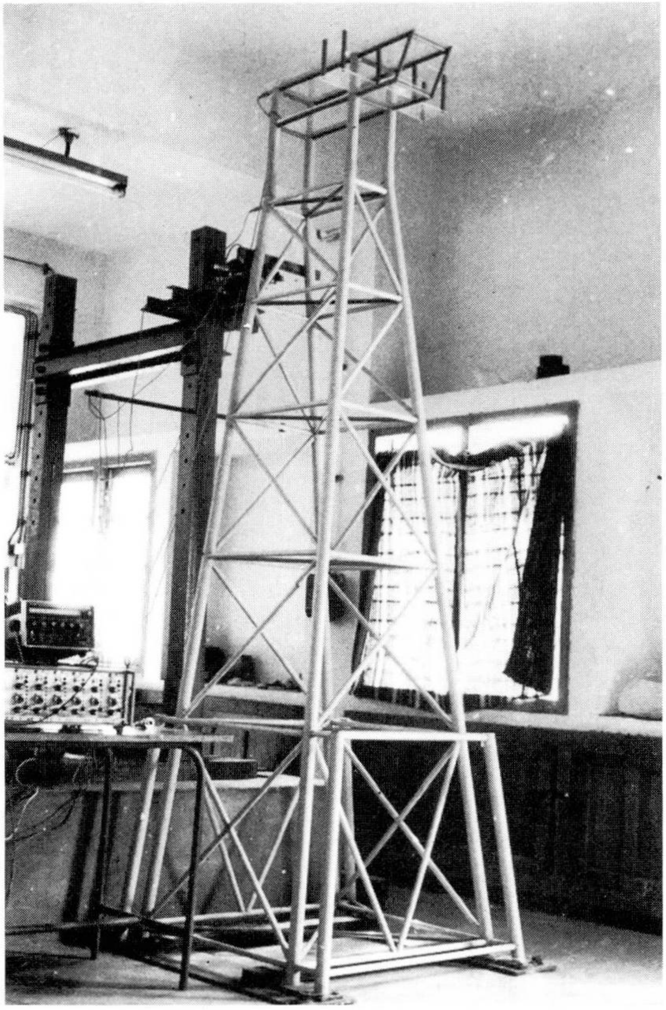


Fig.11
Model under external excitation

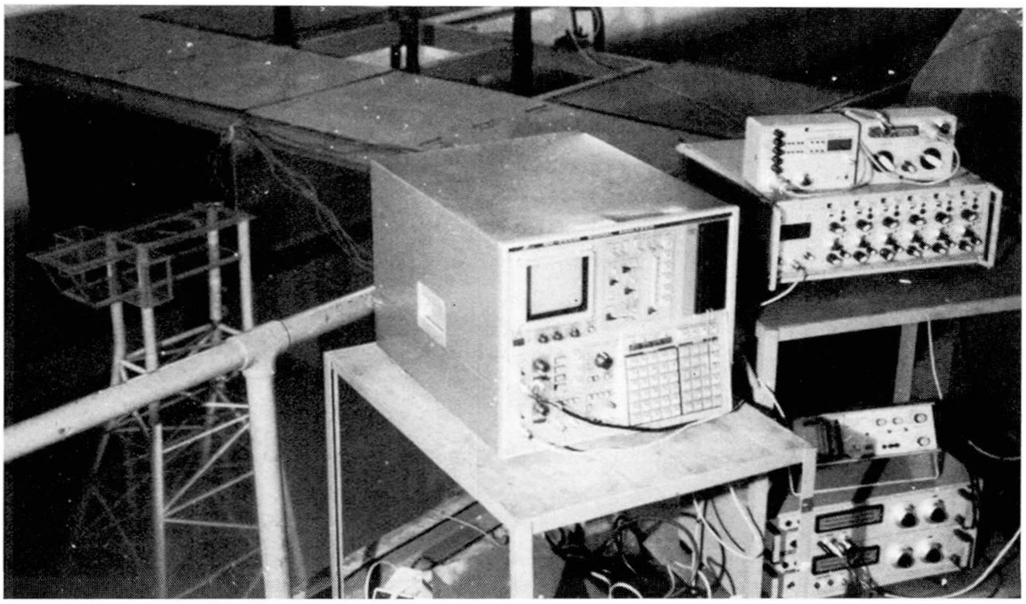


Fig.12 : Model fixed in wave flume for wave loading

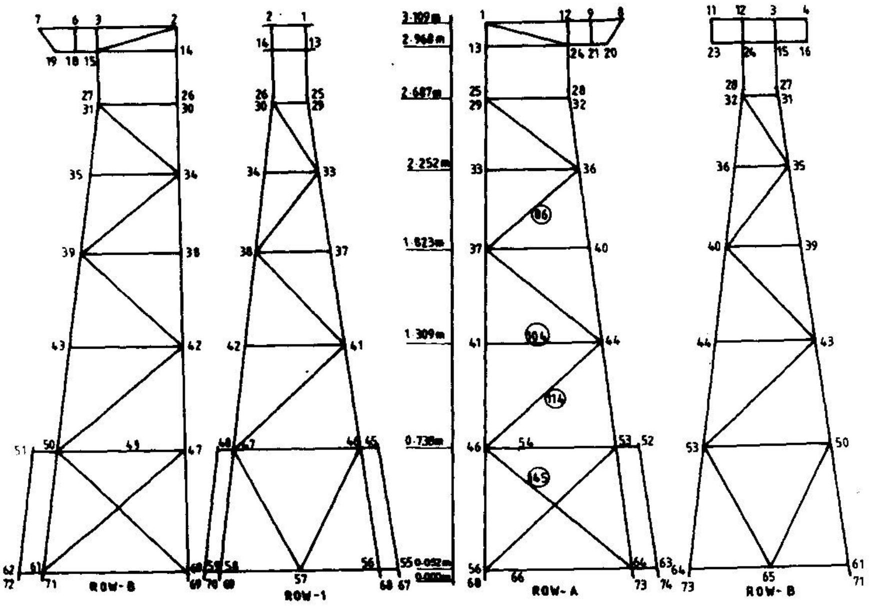
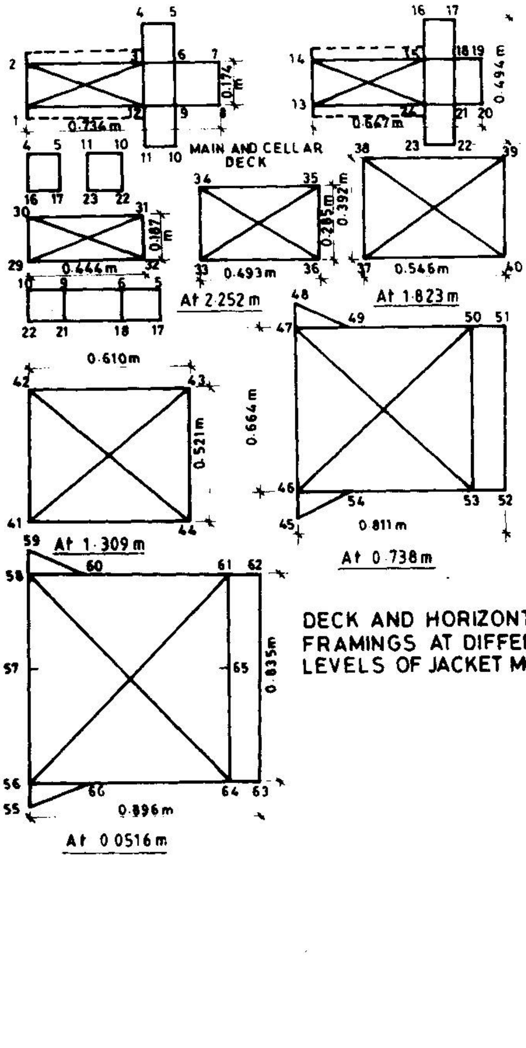


FIG. VERTICAL FRAMING OF JACKET MODEL

Fig.13



DECK AND HORIZONTAL FRAMINGS AT DIFFERENT LEVELS OF JACKET MODEL

Fig.14

Deck Load	Description of Model	Analysis I Flexure	Analysis II Flexure	Experiment I Flexure	Experiment II Flexure
M	No damage	5.727	30.59	5.15	27.5
M	Half through cut 114	5.704 (0)	29.71 (-2.9)	5.15 (0)	26.5 (-3.6)
M	Missing member 114	5.556 (-3.0)	24.13 (-21.1)	4.9 (-4.9)	21.0 (-23.6)
M	Missing member 145	5.708 (0)	29.53 (-3.5)	5.10 (0)	26.2 (-4.7)
M	Missing member 86	5.576 (-2.6)	30.22 (-1.2)	5.05 (-.19)	27.0 (-1.8)
M	Missing Member 104	5.727 (0)	30.57 (0)	5.15 (0)	27.5 (0)
M+10%	No damage	5.457 (-4.7)	30.43 (0)	4.95 (-4.9)	27.0 (-1.8)
M+10%	Half through cut 114	5.438 (-5.1)	29.58 (-3.3)	4.9 (-4.9)	26.0 (-5.5)
M+10%	Missing member 114	5.297 (-7.5)	24.08 (-21.3)	4.65 (-9.7)	20.5 (-25.5)
M+10%	Missing member 145	5.443 (-5.0)	29.46 (-3.7)	4.85 (-5.8)	25.8 (-6.2)
M+10%	Missing member 86	5.334 (-6.9)	30.03 (-1.8)	4.90 (-4.9)	26.5 (-3.6)
M+10%	Missing member 104	5.457 (-4.7)	30.40 (0)	4.95 (-3.9)	27.0 (-1.8)
M-10%	No damage	6.044 (5.5)	30.78 (0)	5.5 (4.9)	27.0 (1.8)
M-10%	Half through cut 114	5.855 (2.2)	29.88 (-2.3)	5.22 (1.4)	27.0 (-1.8)
M-10%	Missing member 114	6.019 (5.1)	24.27 (-20.7)	5.40 (4.9)	21.25 (-22.7)
M-10%	Missing member 145	6.024 (5.2)	29.69 (-2.9)	5.38 (4.5)	26.0 (-5.5)
M-10%	Missing member 86	5.903 (3.1)	30.40 (0)	5.30 (2.9)	27.0 (-1.8)
M-10%	Missing member 104	6.044 (5.5)	30.75 (0)	5.40 (4.9)	27.0 (-1.8)

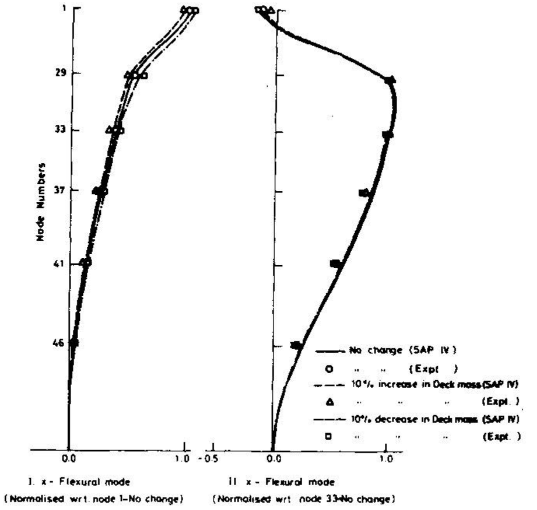
TABLE 8 Natural frequencies in Hz of Model - Comparison of results
Values in bracket give percent change

Mode	Node No	No change		Half through cut in 114		Missing member 114		Missing member 86		Missing member 145	
		SAP IV	Expt	SAP IV	Expt	SAP IV	Expt	SAP IV	EXpt	SAP IV	Ex pt
I Flexure in 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	627.5	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	47.0	47.80		18356.0	9.75	9.33	45.0	42.1	15.75	18.78
II Flexure in X-direction	1	81.33	72.52	13.72	12.53	3.02	2.98	11.86	10.53	22.0	25.03
	29	174.11	195.31	12.03	9.80	2.614	1.88	11.28	8.73	42.8	39.85
	33	75.68	85.66	12.09	11.88	2.84	2.57	16.86	15.88	345.6	402.85
	37	31.54	32.59	13.56	11.77	3.18	2.92	28.30	25.78		14678.5
	41	10.18	9.80	29.43	30.53	3.94	3.24	8.40	7.53	320.5	356.8
	46	17.00	13.59	47.60	50.86	2.47	2.52	12.33	9.79	14.77	16.88

TABLE 9 Ratio x to y translations of I & II mode of model - Comparison of results

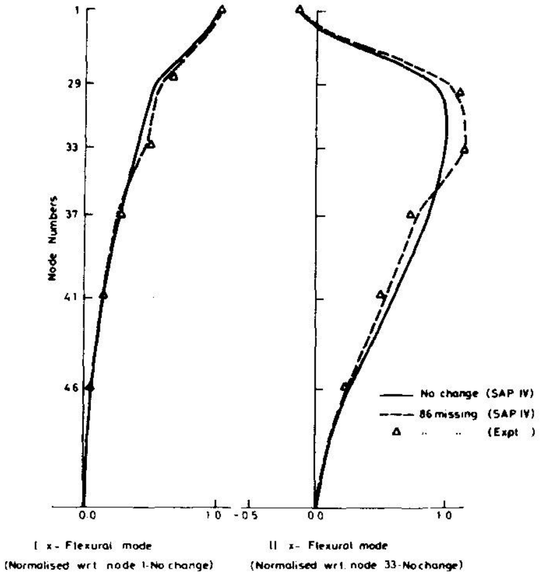
Mode	No change				Missing Member 86				Missing Member 114			
	10 kg deck load		12 kg DL		10 kg DL		12 kg DL		10 kg DL		12 kg DL	
	SAP IV	Expt	SAP IV	Expt	SAP IV	Expt	SAP IV	Ex pt	SAP IV	Expt	SAP IV	Expt
I Flexure in X-direction	4.94	4.25	4.66 (-5.67)	3.95 (-7.1)	4.79 (-3.02)	4.1 (-3.5)	4.52 (-8.46)	3.87 (-8.9)	4.66 (-5.63)	4.02 (-5.4)	4.42 (-10.52)	3.79 (-10.8)
II Flexure in X-direction	13.91	11.55	13.78 (0)	11.5 (0)	13.87 (0)	11.3 (-2.2)	13.74 (-1.2)	11.2 (-2.6)	10.62 (-23.7)	8.5 (26.4)	10.47 (-24.73)	8.5 (-26.4)

TABLE 10 Natural frequencies in Hz of model fixed in water - Comparison of results



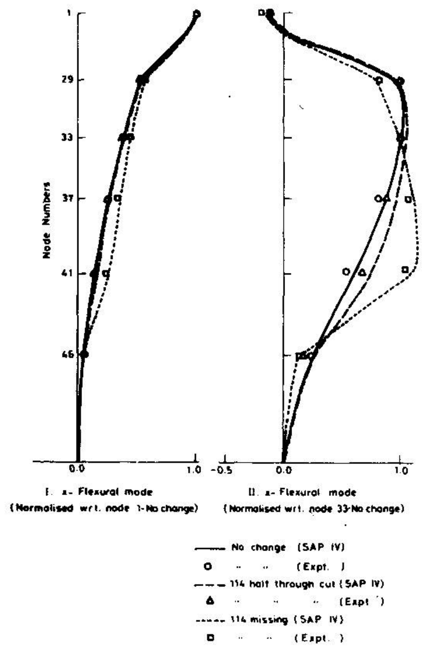
MODE SHAPES-EFFECT OF DECK LOAD VARIATION

Fig.15



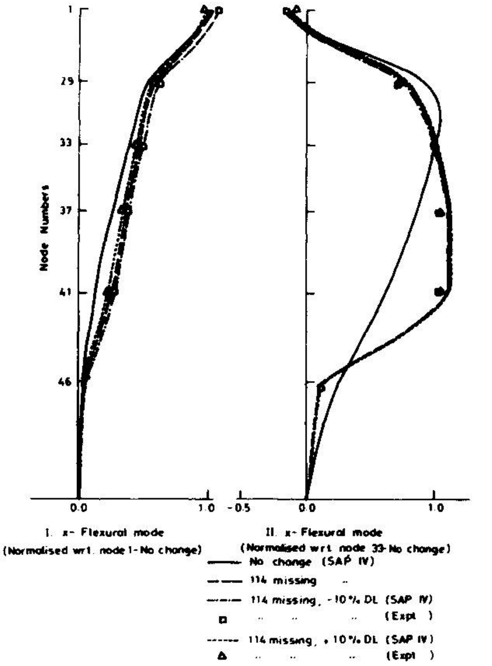
MODE SHAPES-EFFECT OF DAMAGE IN MODEL

Fig.16



MODE SHAPES-EFFECT OF DAMAGE IN MODEL

Fig.17



MODE SHAPES-COMBINED EFFECT OF DECK LOAD AND DAMAGE IN MODEL

Fig.18

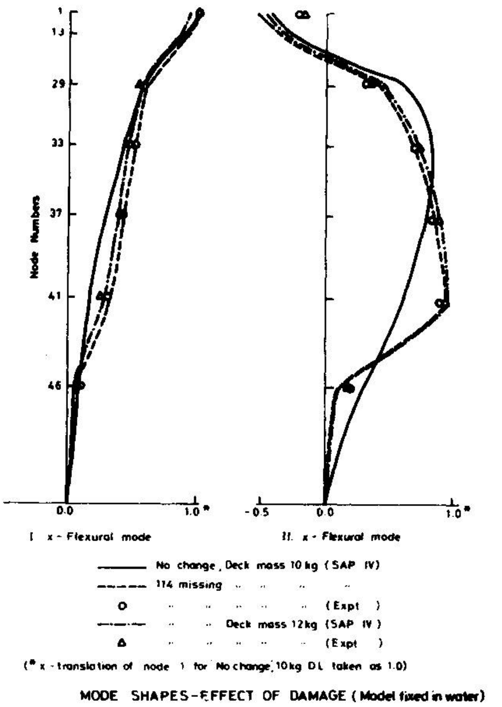


Fig.19

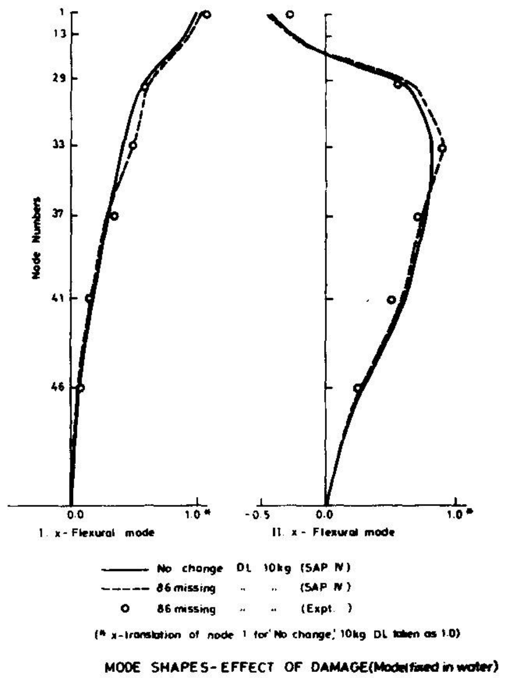


Fig.20

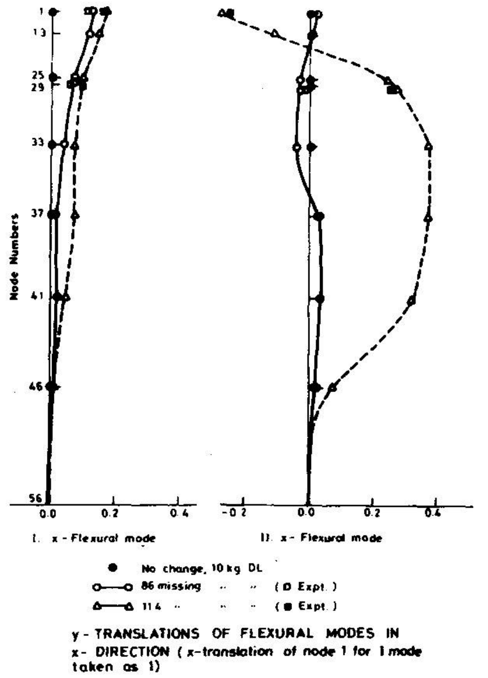


Fig.21

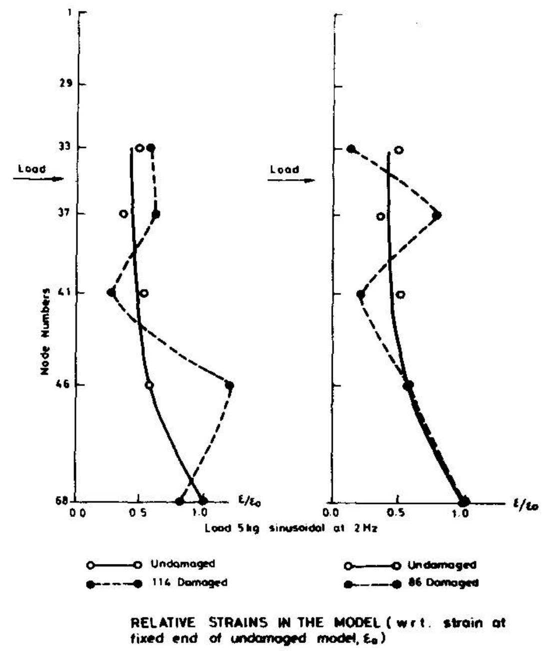


Fig.22

to predominant modal direction can provide very valuable informations with regard to the integrity of the structure. The data from the accelerometers are analysed with the help of a signal analyser having capabilities of auto-spectral analysis of data using FFT or any other proven data processing technique. It is advisable to take this data on all the nodes above water so that identification of modes is possible with the help of phase information. The frequencies thus obtained are compared with those of the analyses and every effort should be made to identify the analytical system which compares well with those of measurement. The next step is the comparison of modal vectors. Modal vectors normalised with some reference points for the predominant modal direction and the direction perpendicular toit should be compared with the theory. If the agreement is good with the identified system, it may not be necessary to venture into any underwater measurements. If the mode shape vectors in different directions are not in agreement, detailed underwater measurement would become necessary. For this purpose too biaxial accelerometers on diagonally opposite legs are to be deployed with the help of divers. If these informations are available (mode shapes) for as many modes as possible, all mode shapes can be plotted and the shape of each can give a good insight into the state of thestructure. As a confirmation, the modal vector perpendicular to the predominant modal direction can also be compared. The main advantage of determining mode shapes with the help of under water mesurement is that, these information can immediately locate the position of damage, if there is any.

4.3 Some additional suggestions

System identification of analytical model with the help of measured data may prove to be the most important phase of this monitoring procedure and perhaps the most difficult. This can however be overcome by taking a complete set of required information on modal characteristics either soon after the installation of the platform or immediatley after a physical inspection by divers. This can form the basis for all future measurements and comparison. If a set of data is available from a healthy platform, it would serve as a signature for comparison for all future measurements.

Temporary deployment of biaxial accelerometers underwater is another difficult phase, and can be criticised as a drawback as in the case of diver inspection. This, however, is not very true because there is a lot of difference between a diver inspecting a structure underwater and installing an instrument for measurements.

At least in the case of new platforms, diver dependence can be overcome, if some accelerometers are installed during the fabrication stage itself. For safety considerations, the most suitable location would be the annular space between the pile and the main leg. Once this area is grouted, the installation will be permanent and development of suitable biaxial accelerometers are well within the reach of the instrumentation industry. Periodic measurements from these accelerometers would be the best indicators of the integrity of the structure and has the potential to replace the physical inspection, if carefully carried out. Though this investigation was carried out with special emphasis on offshore platforms which, except for the deck, is submerged, the method can be easily applied to any tall structure like TV towers, tall chimneys, mooring dolphins, multistoreyed buildings etc. to assess structural deterioration in course of time. A permanent installation to evaluate structural response on these expensive structures can generate valuable data to evaluate the actual factor of safety to help engineers to design economic structures.

5. CONCLUSIONS

Based on a detailed analytical and experimental investigation modal parameters of a well platform has been evaluated and feasibility of its measurement proved.

Simulating various changes in quantities that can affect these parameters, it has been shown that they indicate the integrity of the structure. Based on the investigation, a scheme for integrity monitoring of fixed offshore platforms is proposed which can reduce the frequency of physical inspection, if not completely replace this uneconomical procedure. Of course, these conclusions are based on a laboratory investigation and field measurements on platforms and the capability of the analytical techniques of spectral analysis to determine natural frequencies and magnitudes for mode shape evaluation of as many modes as possible have to be proved to completely exploit the potentialities of this technique. But, if the results available from the reported literature on field measurements on plaform, are any indication, it may not prove to be a very difficult task.

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