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Review of Structural Monitoring

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REVIEW OF STRUCTURAL MONITORING

April 1997

SUMMARY

The structural monitoring of North Sea jackets is reviewed in the context of changes in the technical and operating environment over the last 10 years or so.

The capability of structural monitoring in terms of its ability to detect member severance is assessed by reference to North Sea monitoring projects which have been undertaken. It is shown that single member severance is detectable on non-redundant jackets, while failure of a frame may need to occur before a change is detected on redundant structures.

The effect of technological developments on the equipment for structural monitoring is reviewed and it is concluded that structural monitoring can now be a low cost, low labour activity. Changes in the operating environment including the extension of platform life, inspection philosophy, design and safety are reviewed. Developments in structural analysis, including risk analysis, are assessed.

In the light of changes in the operating environment, and development in structural analysis, a new role for structural monitoring is discussed.

It is postulated that the relationship between the residual strength of a damaged jacket and the loss of stiffness caused by the damage is such that the loss of stiffness will be detected before the residual strength becomes insufficient for safe operation.

If this proves to be the case an active early warning capability is possible and operators will have a low cost, reliable, continuous technique which will ensure safe operation of the ageing and deteriorating assets in the North sea.

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1. INTRODUCTION

1.1. BACKGROUND

For the purpose of this report, Structural Monitoring is considered to be the process whereby response characteristics of a fixed offshore jacket structure are measured (either continuously or at regular intervals) with a view to comparing the measured characteristics with a previously measured baseline or trend. Historically, structural monitoring has been based on the principle that the natural frequencies (and mode shapes) of a jacket structure will change as a result of a reduction in the stiffness of a jacket. Such monitoring has been carried out by some operators on some structures since the late nineteen seventies. However, the North Sea has changed significantly as an oil producing region since that time, so that the environment is now one of mature fields and declining production. Two major changes have taken place in the operating environment. Commercially, the CRINE initiative has focused on reducing costs to maintain the viability of North Sea assets, and in the safety arena the Health and Safety Executive has a statutory role in the management of safety.

As in all areas of life, structural instrumentation technology has developed apace over the last twenty years. In particular, developments in computer and communications technology have had a significant impact on the techniques of structural monitoring.

The design of jackets for the North Sea has also evolved. The commercial pressures of small fields has led to very efficient jacket designs. A controlling factor recently has been the requirement for jacket installation by a single lift. One way of reducing jacket weight is to minimise the number of members. In principle, if a jacket has relatively few members, the loss of a single member has a larger effect on the natural frequencies and should therefore be easier to detect. It is as a result of the changes in practice in the North Sea that it was considered to be of value to review the capability and role of structural monitoring.

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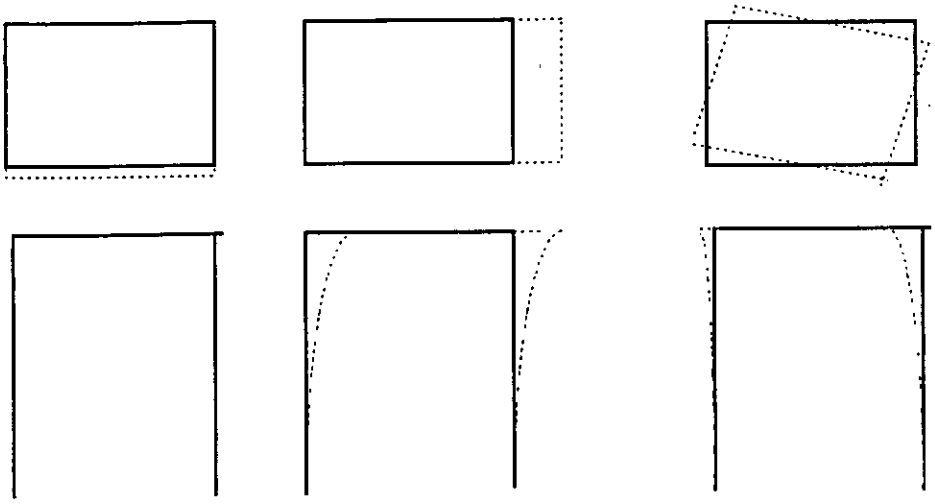
2. HISTORY OF MONITORING IN THE NORTH SEA

2.1. MONITORING PRINCIPLES

A typical Northern North Sea jacket responds dynamically like a beam which is fixed at one end and has a large mass at the other. A series of natural frequencies are excited and each natural frequency has a characteristic mode shape. The mode shapes for the first three natural frequencies of a jacket are illustrated in Figure 1.



NS Sway mode

EW Sway mode

Torsion mode

Figure 1 - Idealised Platform Mode Shapes

Platform natural frequencies and mode shapes are typically measured using sensitive accelerometers. These are mounted horizontally and detect the small sway movements of the platform. These movements occur primarily at the wave period but the platform natural frequencies are usually clearly identifiable as illustrated in Figure 2 - typical spectrum. By measuring movements at different locations on the deck it is possible to distinguish between sway and torsional natural frequencies. Similarly, by measuring movements at different elevations on the jacket it is theoretically possible to distinguish between the first sway natural frequency and higher order sway natural frequencies, although in practice higher order natural frequencies tend not to be strongly excited.

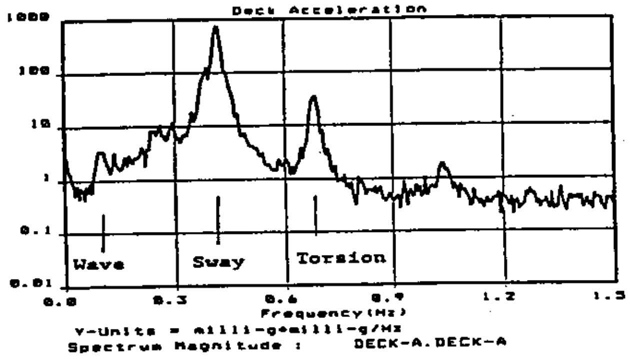


Figure 2 - Typical Platform Response Spectrum (Acceleration)

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A natural frequency and its associated mode shape is controlled only by the distribution of mass and stiffness of the dynamic system, and by the system constraints. If, for example, the foundation stiffness and the system mass can be assumed to be constant, then the natural frequency will vary only with changes in platform stiffness. Under these circumstances the natural frequency can therefore be considered to be a measure of platform stiffness.

This argument can be extended to mode shapes. For example, the ratio of movement of the east face of a platform to the west face will be constant at a particular natural frequency. A member severance on the West face will result in higher flexibility of that face relative to the east, so that the relative movement will increase. Measurements of relative movement can therefore also be used as a monitoring tool. Similarly relative movements of different platform elevations will be sensitive to changes in stiffness between the elevations.

In addition to overall platform natural frequencies, groups of members, individual members etc. will all have their own natural frequencies which, in theory, can be used as monitoring parameters for the stiffness of the structural subset. In practice such groups and members have relatively high stiffness, and the naturally occurring energy of excitation is less, so that measurements of these frequencies may require forced excitation techniques. Using these principles a number of structural monitoring projects have been undertaken in the North Sea.

2.2. OSO RESEARCH PROJECTS

In the late nineteen seventies the OSO commissioned a study to evaluate the potential of structural monitoring. Three companies were commissioned to design and install instrumentation in co-operation with platform operators. The three projects were:

Contractor	Operator , Platform	Basis of System
Structural Monitoring	BP, Forties A	Deck accelerometers
WS Atkins Ltd	Unocal, Heather	Not known
Structural Dynamics Ltd	Occidental Petroleum, Piper A	Deck and extensive subsea accelerometers

Table 1 - OSO Research Projects

It is believed that the latter two projects included a significant quantity of subsea accelerometers, with the objective of measuring changes in relative movement between bays of the jacket. However the cost and maintenance problems associated with such instrumentation has proven to be unattractive to operators.

The Forties Alpha project made use of pairs of accelerometers at deck level, linked to a central processing computer. The system was designed to measure overall jacket natural frequencies and mode shapes. The project also involved the development of a simple finite element model of the platform based on beam elements and lumped masses. This model was used to perform a sensitivity study, in which the sensitivity of the jacket natural frequencies to loss of individual members was quantified. The patterns of natural frequency changes resulting from the loss of members was tabulated in a "failure dictionary" which could be consulted in the event of changes being measured on the structure.

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2.3. OTHER PROJECTS

Major monitoring projects and evaluations of integrity monitoring were also undertaken on a commercial basis in the late 1970's and early 1980's for a number of operators. Important projects included:

BP	Forties B	4 legs-x frame	Joint Industry Study
Chevron	Ninian South	4 legs-k frame	Measurements & Sensitivity Analysis
Chevron	Ninian Northern	8 legs	Short Term Measurements & Sensitivity Analysis
BP	Magnus	4 legs-x frame	Joint Industry Foundation and Jacket Performance Study

Table 2 - Other Monitoring Projects

2.4. OTHER TECHNIQUES

Other approaches to response measurements have also been assessed in the North Sea and elsewhere, including:

Flexibility Analysis:	Use of accelerometers to accurately measure the relative movement of different elevations on a jacket. Various approaches have been used including permanently installed sensors, sensor packages which are regularly run down tubes on the legs, and battery powered systems with cable-less data transmission.
Frame Analysis:	The natural frequencies of individual frames or members are measured using permanent or temporary accelerometers. The natural frequencies are often subjected to forced excitation using a diver or ROV.

These techniques have been developed primarily because it was clear from early studies that topside measurements alone would not detect severance of a single member on highly redundant jackets. There was also the desire to develop efficient crack detection methods at a time when large amounts of MPI and other such inspection techniques were being undertaken.

2.5. CONCLUSIONS FROM PREVIOUS WORK

A number of general conclusions relating to the effectiveness of natural frequencies in detecting member severance can be established from past work. These are summarised below:

2.5.1 Stability of Natural Frequencies

Platform natural frequencies depend, of course, on deck mass as well as jacket stiffness. Other factors may have a secondary effect, including variations in the effective mass of entrained water and non-linearity of foundation stiffness. Further, the mathematical calculation of natural frequencies is a statistical process and each estimate of natural frequency has an associated error. Natural frequency data from continuously monitored platforms is available and can be used to show day by day variations. These are illustrated if Figure 3.

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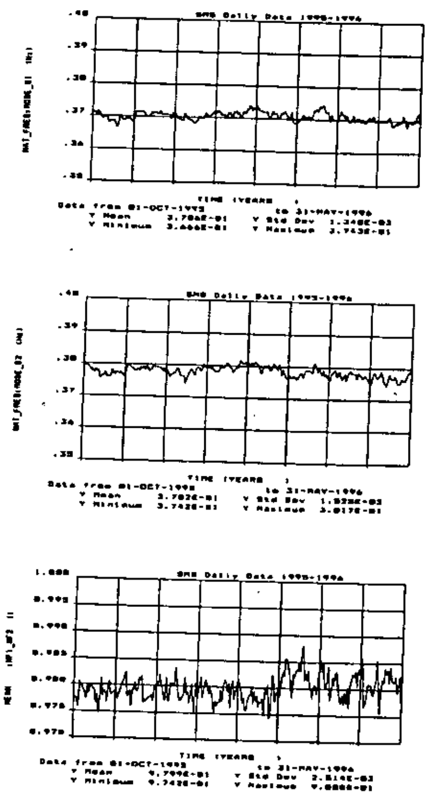

Figure 3 - Daily Natural Frequency Variations

Analysis of one year of such data results in the statistics shown in Table 3 for a typical 4 leg platform

Frequency	Variability
NS Sway	1.1%
EW Sway	1.2%
NS/EW Ratio	0.8%

Table 3 - Natural Frequency Variations Over One Year

The variability is three times the standard deviation of the estimates. Indications of changes outwith the limit of variability can therefore be considered to be significant with a high degree of confidence.

The changes in deck mass should effect the sway natural frequencies of a platform to virtually the same degree. Changes in deck mass therefore result in movements along a forty-five degree line when estimates of NS sway natural frequencies are plotted against EW values measured at the same time. This is illustrated in Figure 4.

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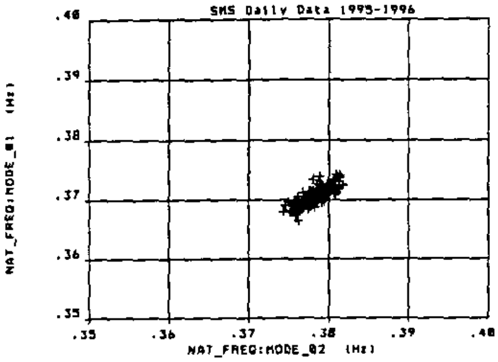

Figure 4 - NS Natural Frequency VS EW Natural Frequency

Since severance of a member will affect the stiffness in one axis of the platform, only one sway natural frequency will be affected. Member severance will therefore result in deviations of the natural frequency estimates away from the best fit forty five degree line. It is therefore the ratio of sway natural frequencies (NS/EW) which is of most value in damage monitoring. The stability of the ratio from the same data is also shown in Table 3.

2.5.2 Sensitivity of Natural Frequencies to Damage

The effect of severance of a single member on the overall natural frequencies will depend on the level of member redundancy of the jacket, and also on the contribution the specific member makes to the dynamic stiffness of the platform at that particular natural frequency. A number of the projects mentioned above have involved the development of simple beam element models of jackets. Using these models the sensitivity of natural frequencies to damage has been assessed for a range of member severances. Indicative results are summarised in Table 4 below:

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Platform and Description	Member Severed	Reduction in Frequency	
		Sway	Torsion
West Sole WE Southern Basin, 4 Leg, K-frame, 3 bays	Main diagonal mid level	3%	10%
	Main diagonal lower level	12%	23%
	Horizontal	1%	3%
Forties A Central North Sea, 4 leg, x frame, 6 bays	One member	1-2% in at least one mode	
	One member	higher natural frequencies 7-16%	
	Panel failure (two members)	at least 1.5% in two modes more than 4.5% in some cases	
	Deck mass changes	Up to 3% (equal in both sway modes)	
Ninian Northern Northern North Sea, 8 leg, diagonal and x brace, 7 bays	Long face Upper level x brace	less than 0.5%	
	Upper level diagonal brace	0.5% to 1.8%	
	Horizontal	nil	
	Short face Upper level, x brace	0% to 0.8%	
	Upper level, horizontal	nil	
	Horizontal plane, internal brace	nil	
Ninian Southern Northern North Sea 4 leg, K-frame, 7 bays	Main diagonal	9.5% - 11.5%	
	Main horizontal	2.5% - 4%	

Table 4 - Sensitivity of Natural Frequencies to Member Severance

2.5.3 Natural Frequencies for Detection of Member Severance

The above discussion indicates that natural frequencies are adequately stable and sensitive to damage that they can be used for detection of changes in stiffness of the order of ± 3% (± 1% change in natural frequency). Severance of a single member can be detected on platforms with low-redundant member configurations, whereas several or many member failures may occur on higher redundant structures before a change is detected. For example, a loss of a diagonal on a K-braced structure results in a frequency change of 9.5% to 11.5% whereas a similar loss on an X-braced structure results in a change of only 1% to 2%. The former is detectable and indicative of a significant loss of overall stiffness.

All the above discussion is based on a continuous monitoring principle. Continuous monitoring is required to allow statistically significant natural frequency estimates to be developed.

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2.6. RESULTS FROM AN ACTIVE MONITORING SYSTEM

Of particular interest in the historical data presented above is that from a conventional 4 leg platform with relatively simple low-redundant bracing. Measurement of natural frequencies were performed while a horizontal member was severed and after its subsequent repair. The member is shown in Figure 5 and the measured data in Figure 6.

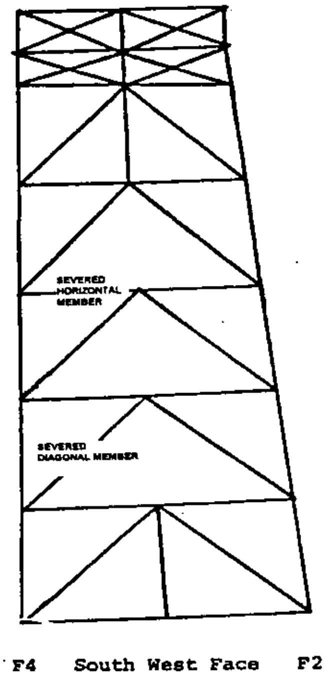

Figure 5 - Severed Members in a Conventional 4 Leg Platform with Monitoring

A finite element study of the platform indicated a reduction of 4.5% in the NS sway natural frequency and about 2.5% in the torsional natural frequency. The measured changes showed excellent agreement and in a blind test it was possible to correctly deduce that a horizontal member had severed in one of three levels.

Severance of a diagonal member in late 1995 resulted in a 10.3% reduction in the NS sway natural frequency. This compared with a predicted value of 10.7%.

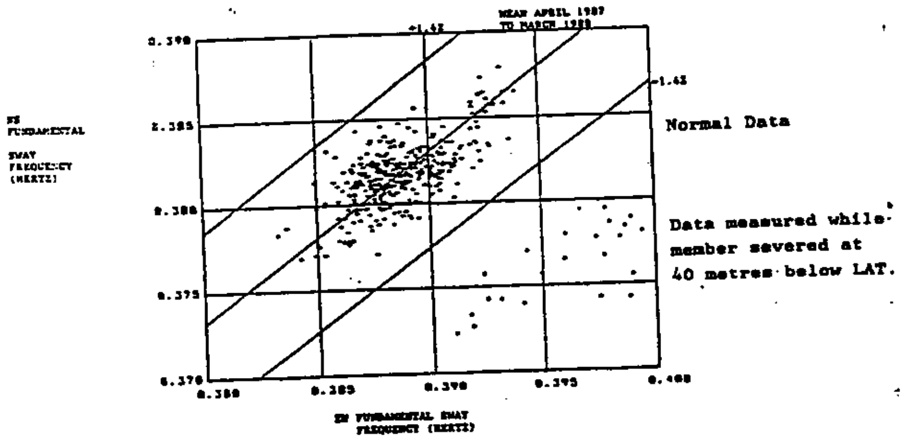

Figure 6 - Effects of Member Severance on NS Natural Frequency

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3. CURRENT TECHNOLOGY AND COSTS

3.1. SENSORS

The principle sensors used for vibration monitoring are servo accelerometers. These are highly sensitive, highly accurate devices developed in the aerospace industry. They have a long record of use in the North Sea and are available in configurations suitable for use in hazardous areas. Subsea configurations are also available.

3.2. DATA COLLECTION

Topside accelerometers are cabled back to a central data collected station using conventional methods. A significant change in recent years has been the development of cable-less underwater sensor packages. These systems are battery powered, and data is transmitted by hydro-acoustic telemetry. A receiver is dipped into the water when data transmission is to take place. There are three reasons why the usefulness of this technology is limited for the structural monitoring application. The equipment must be powered by batteries and even with improvements in this technology the operating capacity of the equipment is limited. This inevitably results in a restricted quantity of collected data, with a resulting reduction in the confidence levels associated with the estimation of parameters. Thirdly the dipping of the receiver may require regular manual intervention. This is considered undesirable by operators for financial and quality reasons.

3.3. DATA PROCESSING

Data acquisition computers have developed in line with the development of technical computers generally. With the addition of an analogue/digital converter board and appropriate software a standard desk top PC can perform the necessary data acquisition, signal processing and archiving. Such a system can be configured for exception reporting so that actions are required only in the event of a significant change in a monitored parameter. Hard disks are also so large that processed data for a year can easily be stored on the system, to be accessed only in the event of a change being registered.

Data collection computers can require no operator intervention whatsoever. It is perfectly feasible to have a small, self contained battery powered unit which can be temporarily placed on the floor in a safe area and switched on to collect and process data over any period.

3.4. COMMUNICATIONS

Communications technology has also shown great advances in recent years. Offshore platforms now generally have very sophisticated communications and are easily contracted by telephone or digital network. Data acquisition computers are easily fitted with modems so that they can be accessed from onshore, either manually or by another computer.

From the above discussion it is clear that technology is now such that topside structural monitoring can be an entirely automatic process with no field action required after system installation. The year on year operating costs can therefore be minimal (less than £ 10,000 at 1997 prices). The capital cost of a system would be less than £ 25,000.

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4. CHANGES IN OPERATING ENVIRONMENT

4.1. CRINE

The North Sea has developed into a mature oilfield and the CRINE (Cost Reduction in the New Era) initiative has been implemented to maintain viability of the North Sea fields in an environment of low oil prices and falling production. Structural Monitoring has not been widely accepted by operators, but the level of interest did fall back after the 1986 oil price collapse. At least one monitoring project was cancelled in mid term in 1986. Operators will now generally spend money when there is a safety issue or when there is a clearly demonstrable cost benefit.

4.2. EXTENSION OF PLATFORM LIFE

While some platforms are subject to detailed decommissioning and removal planning, no platforms have been removed from the Northern Sector of the North Sea. Developments in oil recovery techniques, and radical developments such as the conversion of the Brent field to gas production, have prolonged field life and extended the working life required of platforms. Platforms which were therefore designed for 20 years are now anticipated to have a working life of double that or more.

4.3. INSPECTION

CRINE has also provided a major impetus to review inspection philosophy. Traditional inspection has involved a rolling programme of cleaning, NDT, and crack repair by divers. This was, of course an extremely expensive process and not without safety implications to divers. By adopting a "fitness for purpose" approach to the structural evaluation process it has been possible to reduce and often cease this type of inspection. It is now generally considered that structures are well enough known, designs are sufficiently reliable and construction control sufficient that a combination of visual inspection and flooded member detection is a suitable inspection regime. Some more recent platforms are subject to no annual subsea inspection.

4.4. DESIGN

More recent platforms have been designed with the experience of many years activity in the North Sea. The environment has now been well defined and there is a wealth of data from inspection. There have also been a number of joint industry projects in which the performance of structures has been measured directly. These include Forties B, Magnus and Fulmar. Another significant influence on design in recent years is the weight constrain imposed by installing jackets in a single lift. This has led to very simple structural designs with little redundancy in terms of the number of members. At least one four leg platform in the North Sea has faces with braces in an X-configuration but without horizontal members. Under these circumstances the quality assurance of design and construction must be of the highest order.

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4.5. SAFETY

The philosophy has changed dramatically in the North Sea over recent years. With the advent of safety cases the emphasis is now away from prescriptive regulation to ensuring operations are as safe as is reasonably practicable. This requirement covers structural design, operations, modification, maintenance and repair. The Offshore Installations and Wells (Design and Construction etc.) Regulations 1996 also state that "in the event of reasonably foreseeable damage to the installation it will retain sufficient integrity to enable action to be taken". This has given impetus to research into the ultimate strength of structures and a probabilistic approach to structural analysis (see section 5 below).

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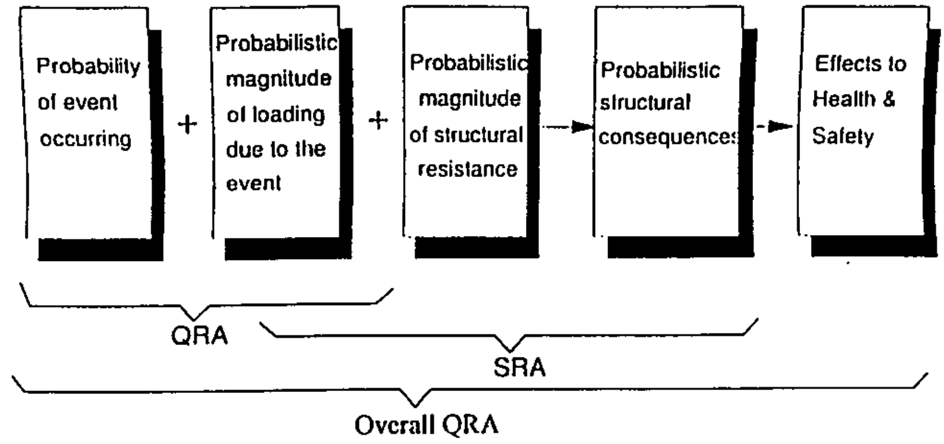
5. DEVELOPMENTS IN STRUCTURAL ANALYSIS

5.1. PROBABILISTIC METHODS

Figure 7 below (Reference 1) summarises the probabilistic approach to structural analysis. By assigning probabilities to events, loadings and structural resistance, the structure can in theory be operated to a specific level of risk. A consequence of particular relevance to the discussion on the role of structural monitoring is that a considerable amount of work has been done on the ultimate strength of structures.



Interface Between Structural Reliability Analysis (SRA), Quantitative Risk Analysis (QRA) and Overall Risk Assessment (Overall QRA)

Figure 7 - Probabilistic Approach to Structural Monitoring (Summary)

5.2. ULTIMATE STRENGTH ANALYSIS

Sophisticated definitions of redundancy have been developed to take account of the likelihood of progressive collapse under different loading conditions. Residual strength is also defined in terms of the environmental load at collapse of a damaged structure divided by the environmental load at collapse of an undamaged structure (Lloyd and Clawson 1984). Similarly, the redundancy factor is defined as the ratio of ultimate strength to design strength. The objective of this type of work is, of course, to be able to assess the fitness for purpose of a damaged structure. A review of the subject (Reference 2) concluded that the subject is relatively new and there is a need to devise a procedure for modelling and evaluating structural reserve which will have industry wide agreement. Significant effort is being expended in this area and an historical overview is given in Reference 3.

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6. DISCUSSION, MONITORING IN THE MODERN CONTEXT

6.1. DETECTION OF SEVERANCE

The conventional view has been that the sensitivity of natural frequencies to member severance is very much as would be expected by review of the structure member configuration. Jackets with low-redundant configurations will be amenable to monitoring, while high-redundant jackets may require the severance of two members in the same frame before a detectable change occurs. What is clear is that design standards and methods used to date have resulted in significant differences in interpretation of redundancy requirements.

The changes in the operating environment in the North Sea have led to a change in inspection philosophy. There has been a move from detailed inspection based on ranking of joints by fatigue lives calculated using simple SN calculations to a probabilistic inspection planning approach.

This goal based approach allows a level of imperfection in structures, as long as the overall level of safety is acceptable. In this environment it is possible that the role of structural monitoring can be redefined.

6.2. STIFFNESS VERSUS STRENGTH

Structural monitoring is used to monitor stiffness changes in a structure. However, the safety issue is whether the structure has sufficient residual strength for safe operation for repair decision making to be taken in the event of a change of stiffness. The argument can be made in the opposite sense in the form: “Is there any need to be aware of structure deterioration if it is less than the detectability threshold of the structural monitoring technique?"

A detailed review of residual strength investigations has been carried out (Reference 2) with the objective of deriving information on the reserve strength of structures. This review yields limited useful information on stiffness changes associated with changes in ultimate strength. A number of the studies primarily based on full 3-D jacket models show sufficient reserve capacity for safe operation of structures which have had a member severance, when all the non-linearity and geometric attributes of a structure are modelled. Thus it is not just the value of reserve that is important but also how that value is achieved. One measure of this may be investigated by reviewing loss of stiffness implications.

It may therefore be possible to assess the suitability of a structure for monitoring in terms of its redundancy factor after the occurrence of damage. This is illustrated in the idealised graph below (Figure 8).

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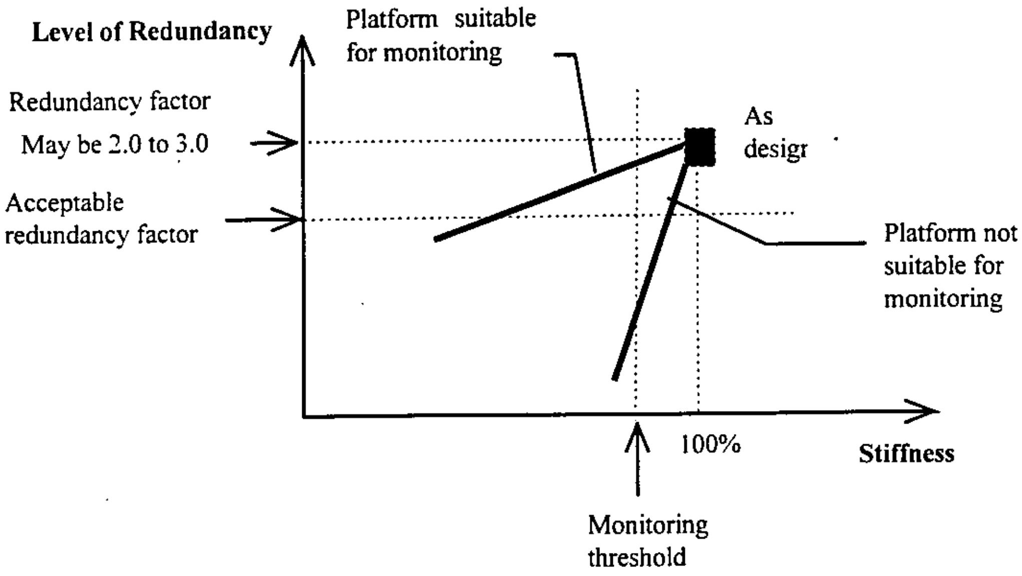

Figure 8 - Redundancy vs Stiffness Concept for Steel Jackets

Platforms will be suitable for monitoring if any member failure or combination of member failures which puts the structure into an unsafe condition will result in a change of stiffness of about 3% or more. This is a development of the approach adopted in the past where, if member severance was detectable then structural monitoring was considered viable.

It may be the case that very many North Sea platforms are suitable for monitoring on this basis. However, it has already been recognised that there is a need for industry-wide consistency in evaluating system reserve and consistent information may not be generally available.

6.3. THE ROLE OF STRUCTURAL MONITORING

The above discussion suggests that structural monitoring has the potential to have a role beyond that of simple member severance detection. Instead, it may be the case that as long as the stiffness of a jacket does not change sufficiently to be detected, then there will always be an acceptable level of redundancy in the structure.

Further, in cases where single or multiple member severances render a platform unsafe, structural monitoring may give first warning of this condition. Such monitoring can be performed continuously, in all weathers. The cost and logistics of the process are such that monitoring is "reasonably practicable".

Structural monitoring will function irrespective of whether the source of a platform change is due to environmental factors or external factors. Using the technique can be though of as cutting off some of the tails of a multi-variate probability distribution by ensuring that warning of an unsafe condition is given. This is consistent with the trend to risk based techniques in structural integrity management.

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6.4. FUTURE DEVELOPMENT

The approach developed in section 6.2. above can be evaluated for specific cases in the North Sea. The Ninian Southern platform is an example of a relatively low-redundant jacket (simple K-frames) which has a long history of monitoring. Some limited monitoring work has also been done on the Ninian Northern platform, which has a much higher level of member redundancy. It would be instructive to perform or review redundancy analysis on these jackets to assess whether the relationship between redundancy and suitability for monitoring exists. Further, it may be possible to study some of the residual strength work reported in reference 2, to establish the stiffness changes associated with relevant redundancy studies. Where the relationship does exists between residual strength and stiffness operators will have an extremely low cost addition to the structural assessment armoury. This could have a significant effect on the ongoing inspection costs both of ageing and relatively new structures.

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7. CONCLUSIONS

It is shown that natural frequency monitoring is a cheap and reliable method of detecting changes in platform response which equate to changes in stiffness of the order of 3%.

This level of stiffness change is sufficient to detect severance of main members on many configurations of jacket, but will equate to severance of several members on redundant configurations.

It is postulated that for North sea platforms, a detectable level of stiffness change will occur before the residual strength becomes critical. Further study on the subject is advocated.

Where a suitable strength/stiffness relationship is demonstrated structural monitoring has the potential to provide a very low cost, reliable, continuous technique which will ensure safe operation of ageing and deteriorating assets in the North sea.

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